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INTERACTION OF TURBULENT AIR JETS WITH AN IMPINGING REACTING STREAM - AN APPLICATION TO AN ADVANCED AIR BREATHING PROPULSION SYSTEM

By

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SUBSONIC RAMJET COMBUSTION
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An important practical application of the interaction of turbulent air jets with an impinging reacting stream is described in this report. A system of cross-jets located upstream of the sudden expansion step of a dump burner is able to amplify the recirculation zone thereby increasing the flame spreading as well as the characteristic residence time. Furthermore, the cross-jets with mass flow rates in the range of 1% to 4% are able to smooth out rough burning in a small volume-limited burner without any additional drag penalty. The lean blow off performance, rough burning, flow field characteristics and preliminary scaling -

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ABSTRACT

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ACKNOWLEDGEMENT

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I. INTRODUCTION

Recently a great deal of emphasis has been placed on developing compact, smooth burning, advanced air breathing combustors with low pressure loss, high degree of reliability and improved combustion efficiency. A sudden expansion burner or the so called dump combustor concept has been proposed as a possible candidate for such an advanced propulsive system. The well proven bluff body flame holders are not quite suitable because of the large pressure drop associated with the typical blockage area required for an efficient operation. Even though all flame holders and combustors utilize flow separation and fluid recirculation, Reference 1 appears to be one of the first attempts to classify a sudden expansion burner as a "recessed wall" flame holder. Experiments show that these flame holders have low pressure drop* and wide flame blow off limits. However, the flame spreading is very inadequate and the combustor requires an excessive length before the flame can spread throughout the entire flow field. Thus, in spite of certain advantages, such a flame holder can not

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* 1" of water at 250fps vs 13" of water for a bluff body flame holder with 37% area blockage (Ref. 1).

obviously meet the requirements of the advanced burner concept. Another concept, an opposed jet flame holder (References 2 and 3), appeared to have a good flame spreading, low pressure drop and also a fairly wide flame blow off limits. Unfortunately, the blow off limits were found to be extremely sensitive to the angular orientation of the jet. For example, a misalignment of only about 10° between the primary flow and the jet caused a 40% degradation in the maximum blow off velocity (Reference 4.) Therefore, in spite of all the advantages, an opposed jet flame holder can be eliminated from any serious consideration.

Since both of these devices have excellent flame holding characteristics and inherently low pressure drop, a combination of these two might prove to be the desired flame holder. Such a modified dump combustor will posess all the advantages of both and none of the disadvantages.

This report describes a study of a modified dump combustor where a cross-jet of air in the immediate vicinity of the step is allowed to interact with the primary flow of combustible mixture. The interaction between the vortices induced by the turbulent cross-jets and the sudden expansion step causes a substantial increase in flame spreading without sacrificing the overall flame blow off performance (Reference 5.) Moreover, the vortices induced by the gas jets act as a fluid amplifier and significantly increase the size of

the recirculation zone. The use of these gas jets helps create a unique, small volume combustor whose flame spreading and the recirculation volume can be modulated by controlling the momentum flux of the jets.* (References 6 and 7.)

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* Typically the total jet mass flow rate is of the order of 4% of the primary flow rate.

II. CROSS-JET SYSTEMS: SLOT JET vs DISCRETE HOLES

2.1. Experimental Apparatus

Most of the experiments were performed in a [illegible]" x 1" quasi two dimensional channel burner with two 3" x 6" vycor glass windows (¼" thick). Figure 1 is a photograph of the test chamber located in the Combustion Laboratory of the Mechanical Engineering Department of the University of Southern California. The air for combustion is supplied by a Paxton Centrifugal Blower with a capacity of 30 lb/min of air at slightly over the atmospheric pressure. The stagnation temperature is of the order of 130°F. By means of a different blower pulley it is possible to nearly double the flow rate. Commercial grade propane is bled into the system through a small tube with many holes located about 4.5 ft ahead of the test chamber to insure complete mixing. The combustible mixture is ignited by means of a 10,000 volt spark device located upstream of the sudden expansion step (Fig. 1). A rectangular plenum chamber serves both as a sudden expansion step and air supply point for the cross-jet system located upstream of the sudden expansion section. The planum chamber can be raised or lowered to provide different step heights for the sudden expansion burner. The cross-jet system, on the upper surface of the

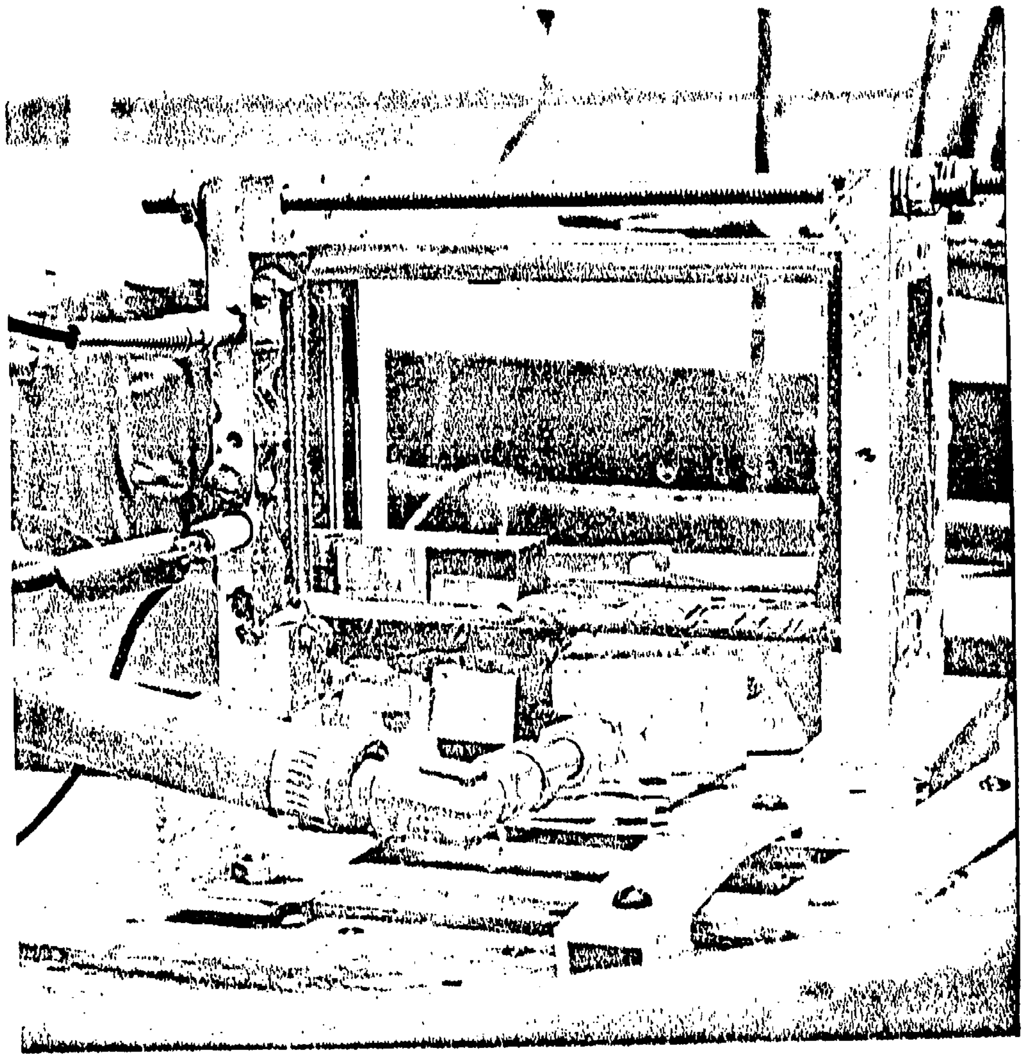
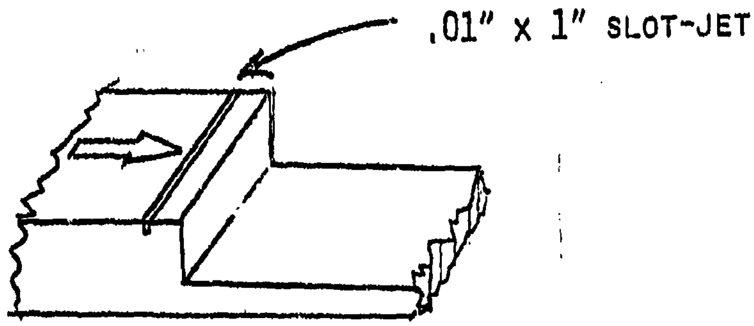


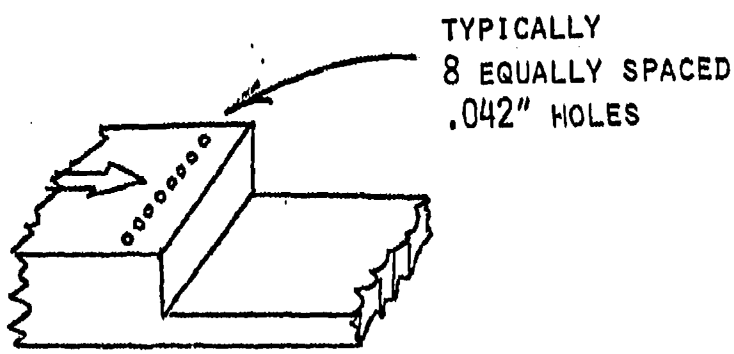
FIGURE 1 Photograph of the Combustion Chamber

rectangular block, consists of either a narrow slot or a set of discrete holes. Different blocks are used to vary the jet size and its location relative to the dump plane. Figure 2a shows the sketch of a typical slot-jet and Figure 2b shows a cross-jet system with discrete holes.

The burner design permits inclusion of steps and jets both on the upper and lower walls of the chamber. It is also possible to operate only one set of cross-jets in a chamber with two sudden expansion steps. In addition to these, provisions are made to operate the burner without any step at all i.e., by means of only cross-jets on a flat plate. Figure 3 show the sketch of a typical channel burner with a movable 30° ramp simulating a nozzle. Both the location and the thickness of the ramp can be changed as the need arises. Thus, the nozzle location and nozzle to chamber area ratio can be varied and their effect on the burner performance can be studied. Microphones and pressure transducers can be attached on the upper wall directly above the recirculation zone to measure the pressure fluctuation in a combustor of small volume where the nozzle is closer to the dump plane. Pressure fluctuations over a preselected frequency band are measured by means of a tunable band pass filter, brush recorder and a sound level meter.



A) SLOT-JET SYSTEM



B) DISCRETE HOLES

FIGURE 2 Typical Jet Systems

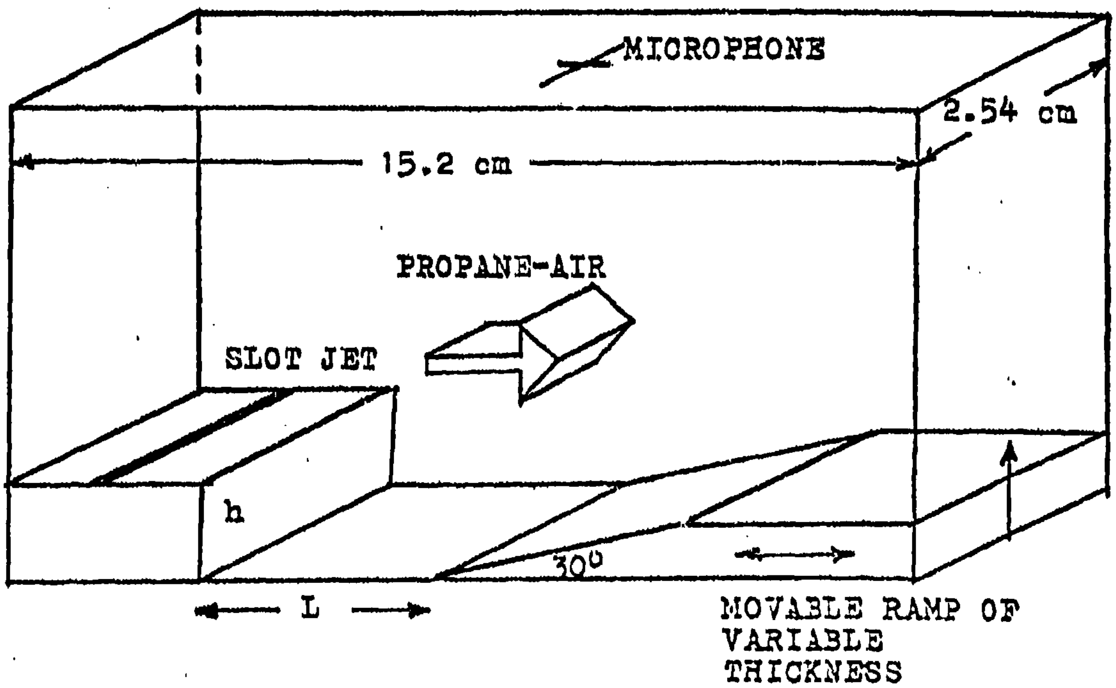


FIGURE 3 Sketch of a Channel Burner with a Movable Ramp

Mass flow rates of the primary air, gaseous propane and the jet air are measured by means of calibrated venturi meters. The upstream stagnation pressures of the jet air and propane are controlled by means of pressure regulators. Because of impurities in the commercial grade propane and laboratory air supply, heavy duty filters are incorporated in the supply lines.

For the channel burners a large portion of the combustible mixture leaves the system in an unburned state. To prevent further combustion downstream, water is sprayed at many locations inside the 12" diameter steel exhaust pipe. However, in spite of the water spray, the exhaust system was found to be inadequate for performaing rich flame blow off. The unburned combustible mixture tended to ignite inside the pipe and flash back upstream possibly through the boundary layer. Similar difficulty was encountered at higher speeds even for lean blow off in the case of a 8" x 1" channel burner. Thus, the present 12" diameter exhaust duct is not very suitable for channel burners of that size.

2.2. Flame Blow off and Spreading

The objective of the first phase of the experimental program was to obtain flame blow off data for various step heights h and determine the flame spreading characteristics. It was essential to find if there exists a critical step

height for the 3" x 1" burner beyond which the blow off limits are insensitive to the step height. Since flame stabilization process is dependent upon the recirculation zone downstream of the step, cold flow experiments and water table experiments were simultaneously performed to study the recirculation length. Cold flow experiments consistently showed that for a two dimensional channel flow, the reattachment zone of the separated flow is between 6 and 7 step heights downstream. Similar behavior of the recirculation zone during burning was also observed by means of a probe coated with NaCl solution. The distance to the reattachment point is a critical parameter for studying rough burning caused by the nozzle located too close to the step inside the recirculation zone.

Figure 4 shows the flame blow off limits of several step configurations, ¼" x ¼";* ½" x 0; ½" x ¼" and 3/4" x 0. For all cases, the ramps were located downstream of the reattachment point. The L/h ratio (L = distance to the ramp, h = step height) for these steps were between 8 and 9. These values were large enough so that no geometric constraint was imposed upon the recirculation zone. Also the recircualtion volume was large enough to sustain stable

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* The first dimension is the step height and the second dimension is the height of the ramp (Fig. 3).

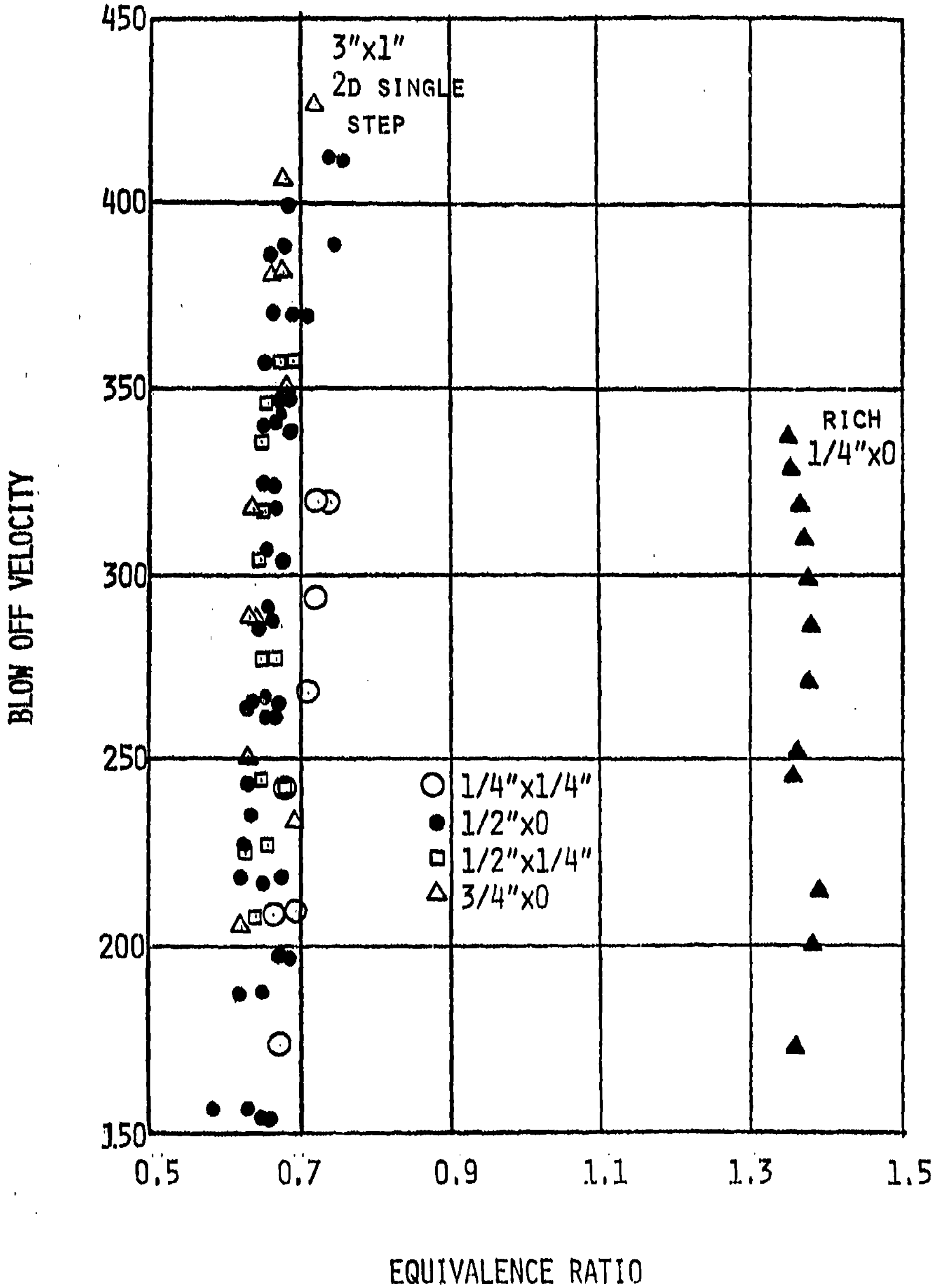

FIGURE 4 Flame Blow off Limits for Various Step Configurations. First Dimension is the Step Height and the Second Dimension is the Ramp Thickness

burning. The results of Fig. 4 indicate that for the present 3" x 1" combustion chamber the lean blow off limits are roughly independent of the step size between 1/4" and 3/4". A step size smaller than 1/4" causes the lean blow off performance to be considerably degraded. Only one set of rich blow off experiment (in Figure 4). was attempted. Because of the design of the exhaust duct it was necessary not to try to establish rich blow off limits.

During the second phase of the program, a slot jet of air (Fig. 2a) in the vicinity of the step was utilized to study the degree of flame spreading and the blow off performance of the burner. The addition of such a jet system, considerably increases the number of possible variables which can affect the behavior of the system. For example, the composition of the gas jet, its temperature, pressure, velocity, mass flow rate, position with respect to step, slot width and the jet angle can have a progound influence upon the system performance. In order to reduce the number of variables, a choked air jet at room temperature aimed normal to the primary flow direction was selected. Thus, the slot width, jet pressure, mass flow rate, jet location, step height and the position of the nozzle were varied. Flow visualization by means of soap bubbles and fluid injection under cold flow conditions

were carried out simultaneously to help select the optimum configuration. These cold flow experiments gave a qualitative picture of the interaction of the vortices induced by the jet and the step.

Figure 5a shows the flame spreading of a typical sudden expansion configuration of ½" x ½". Dramatic increase in flame spreading due to a choked .01" x 1" slot* jet of air is shown in Figure 5b. Typically, the jet mass flow rate is between 1% to 4% of the primary stream for the optimum operation of the present 3" x 1" dump burner. For other chambers of different cross sectional area, it is believed that the mass flux† ratio will be a more appropriate parameter. The optimum mass flux ratio for the present jet system is between 3 and 11. Even though mass flow rate will be frequently referred to in this report, the mass flux ratio and the momentum flux ratio are more pertinent.

Figure 6 show the effect of the location of the jet x_j (from the dump plane) on the flame plume in a 3" x 1" combustor. These are obtained from a photographic study

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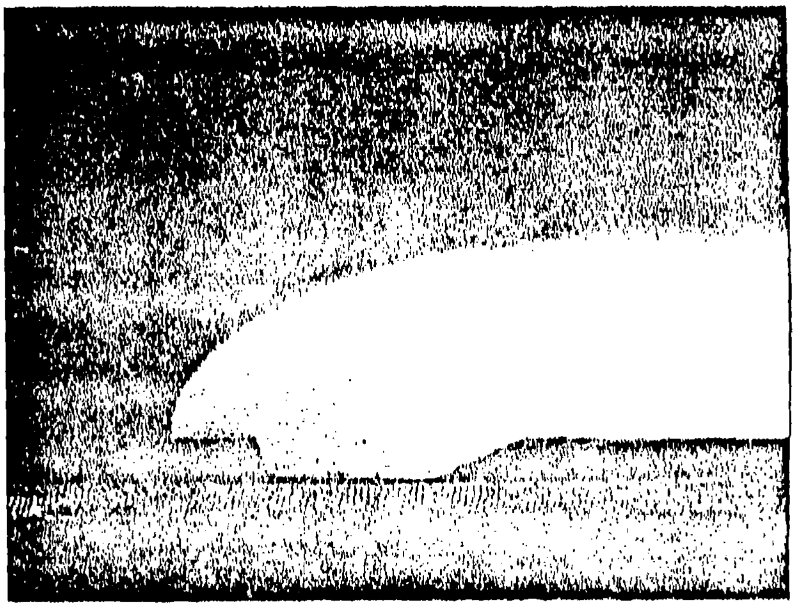
* Preliminary tests indicated that a slot width of .01" had a better overall performance.

† Mass flux = mass/(area - time). Mass flux ratio = (mass flux of jet)/(mass flux of primary stream).

a) 1/4" x 1/4" step. $L/h = 4$, $U_o = 250$ fps



b) .01" x 1" slot-jet $\dot{m}_j/\dot{m}_a = .04$, $L/h = 4$, $U_o = 250$ fps

FIGURE 5 Flame Spreading Caused by an Air Jet

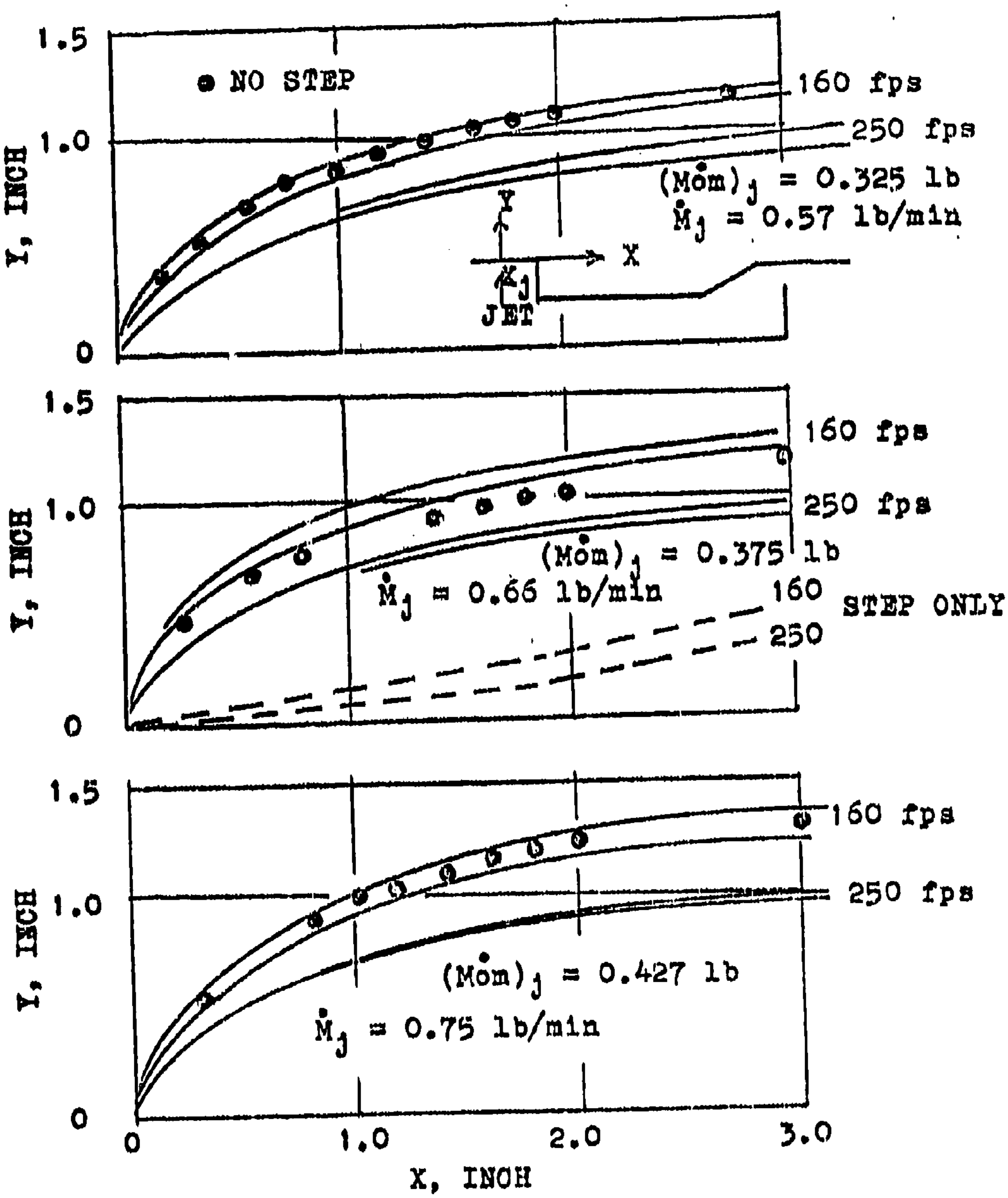


FIGURE 6 Flame Plumes with Different Jet Location

of the .01" x 1" slot jet system. Data for three different jet momentum rates indicate that the shape of the flame is independent of the location of the jet and depends upon the momentum or mass flux ratio. The flame plumes with the jet on a flat plate without any step ($x_j = \infty$) are practically the same for any combination of x_j = 0.1", 0.5" and 0.9"; and the step height h= ¼", ½" and 3/4". Figure 7 is a cross plot of the plume data showing the flame penetration 3" downstream of the step as a function of the momentum flux ratio. Flame penetration 3" downstream of the step reaches nearly the maximum value (Fig. 5b). At a given momentum flux ratio, the flame penetration is independent of the step height and the location of the jet upstream of the step. Pleminary investigation had shown that the jet system is effective only when located upstream of the step. Hence all x_j values refer to the distance upstream of the step. Flame penetration for a cross-jet system with 8 equally spaced 0.042" discrete holes are also shown in Fig. 7. In addition to the flame data, jet penetration results with bubbly soap solution streaking past the chamber wall are shown in Fig. 7 Both slot-jet and cross-jet systems have nearly identical flame plumes when the momentum flux ratio between the two systems are the same. Because of higher inertia, the jet penetration in cold flow is larger.

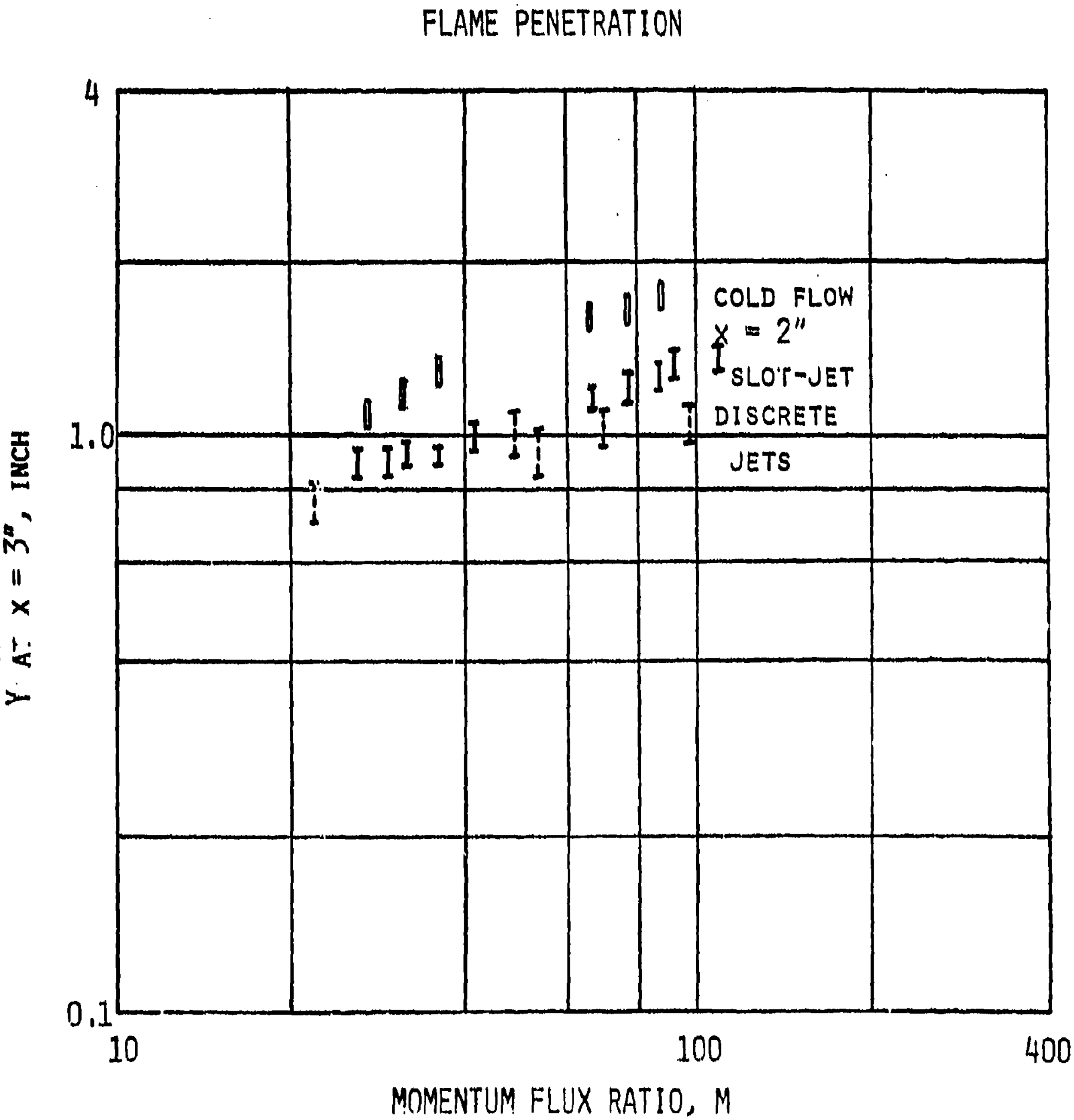


FIGURE 7 Flame Penetration due to an Air Jet for x_j = 0.1", 0.5", 0.9" and ∞ with Various Step Heights

The flame blow off performance of a typical slot-jet system with different jet location and step height is given in Figure 8. Similar to the flame penetration, the lean blow off limit, in spite of data scatter, seems to be independent of the location of the slot-jet as well as the step height. For experimental convenience a constant value of $\dot{m}_j/\dot{m}_a$ was maintained rather than a constant value of the momentum flux ratio. For a constant $\dot{m}_j/\dot{m}_a$ (also the mass flux ratio) the location of the jet and step size are inconsequential. However if only a constant jet mass flow rate $\dot{m}_j$ is maintained, the blow off limit is affected by the jet location. The fact that under controlled conditions the flame spreading and the lean blow off limits appear to be independent of the step height and geometry is rather significant in understanding the role of the air jet in a dump burner. Observations show that the interaction of only the air jet with the primary combustible mixture is the dominating mechanism. The geometric details of the downstream are of little consequence in pridicting both the blow off limits and flame spreading. Such a strong influence of the jet on the flow stream has been observed also in cold flow experiments. Priliminary flow visualization studies with soap bubble indicated that the jet, in effect, increases the size of the recirculation zone downstream of the step. More detailed experiments on the

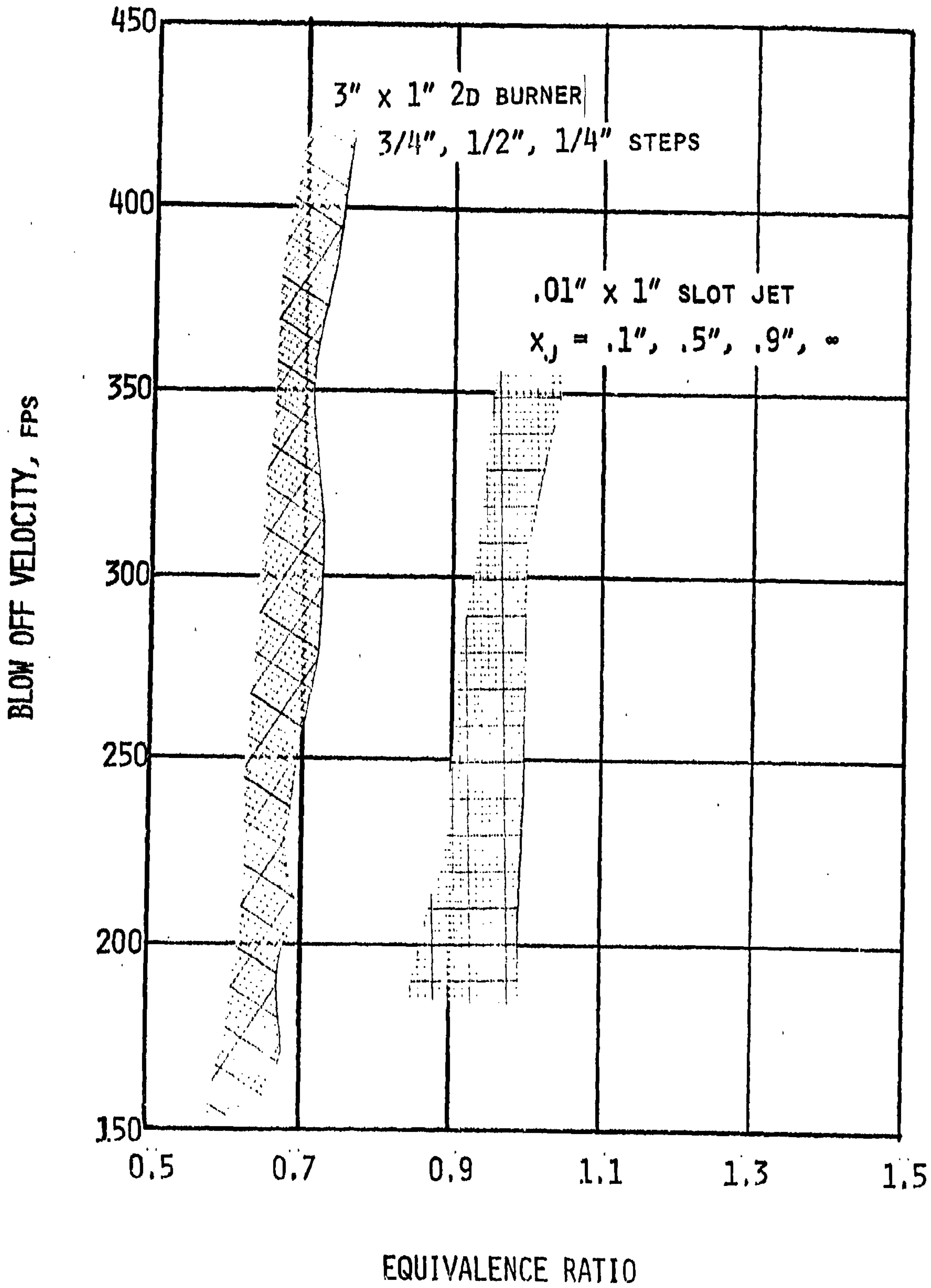


FIGURE 8 Flame Blow off Limits with a Slot-jet System

phenonomenon of amplification of the recirculation zone by means of cross-jets are discussed later in Chapter IV. The role of the jet system as a fluid amplifier is further substantiated by utilizing the jet to smooth out rough burning in a simulated volume-limited combustor.

The lean flame blow off limits with a slot-jet show higher overall equivalence ratios compared to a dump burner without any jet. This is primarily due to the local dilution caused by the air jet. The combustible mixture must penetrate the jet plume and travel through the boundary layer at the wall to reach the dump plane. The blow off performance of Fig. 8 does not show the sensitivity of a given configuration to sudden small changes of operating conditions. The flat plate with a slot-jet, for example, is rather sensitive to changes in the upstream velocity or the mixture ratio even through its lean blow off limits are very similar to the other configurations. A slot-jet located at $x_j = 0.5"$ appears to provide the best performance in the 3" x 1" chamber with a single step. Also $\dot{m}_j/\dot{m}_a$ values between 1% to 4% seem to be the optimum jet mass flow rate. The burning becomes rough, in many cases, when this value exceeds 5%.

From the view point of mechanical design and added fuel requirement, the slot-jet system is not very realistic. A cross-jet system with 8 equally spaced 0.042" diameter

holes over the 1" width of the step was investigated next as an alternative to the slot-jet system. As was indicated earlier (Fig. 7) the flame penetration with a cross-jet system is similar to that of a slot-jet system. Even though the maximum flame height seems to scale with the momentum flux ratio, excessive amount of jet air induces rough burning possibly because of local lean blow offs. Therefore, there is a practical limit to the degree of flame spreading one can obtain in an air jet system. The system behavior is expected to change considerably if heated air, oxygen or combustible mixture is introduced with the jet. Drastic changes have been reported in Reference 8 when different gases were injected in the recirculation zone behind a bluff body flame holder. No attempt was made, however, to study different gas jets other than air at room temperature.

Lean blow off performance with a jet system consisting of discrete holes is compared with the other systems in Figure 9. The equivalence ratios at the lean blow off are considerably smaller than those of the slot-jet system. They are, however, slightly larger than those of a dump burner without any jet. In addition to the local dilution of the combustible mixture, the heat transfer from the primary stream at 130°F to the cold jet air at 70°F is responsible for the difference in equivalence ratio at

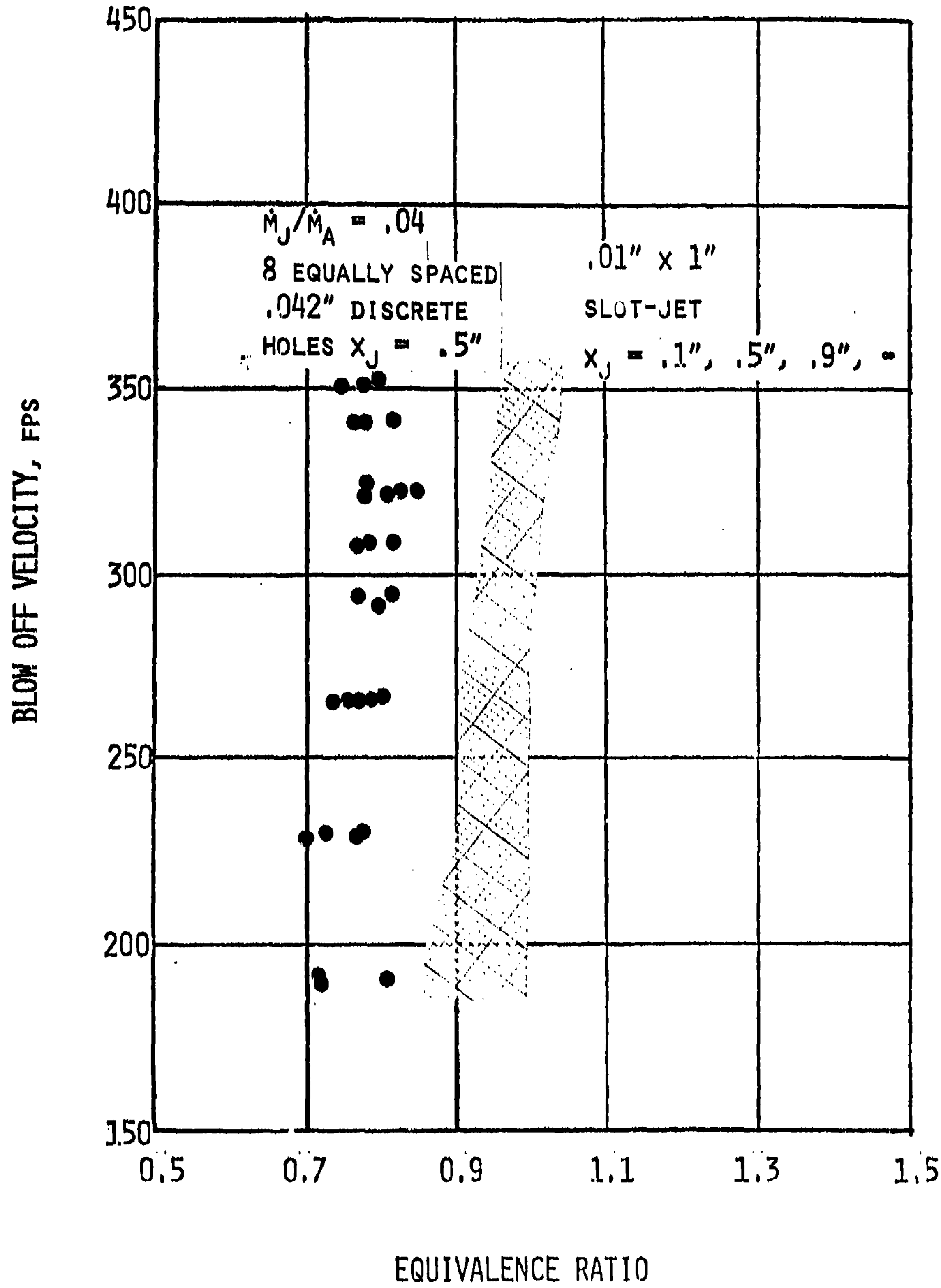


FIGURE 9 Comparison of Blow off Performance of Jet System

blow off. The difference is expected to decrease if the jet air is heated to 130°F.

Since the jet system is choked, for a given valve setting the mass flow rate can be changed by changing the supply pressure. Upstream stagnation pressure was arbitrarily varied from 15 psig all the way to 60 psig. As long as the mass flux ratio corresponding to $\dot{m}_j/\dot{m}_a$ of around 4% was maintained no perceptible difference in the blow off performance was observed.

2.3. Fuel Stratification

One of the primary reasons for fuel stratification in an engine is an incomplete evaporation and mixing of fuel spray due to an inadequate residence time. Such a situation arises in combustion chambers of small characteristic length. Because of the locally fuel-rich state, the blow off limits might show anomalous behavior similar to those reported in References 5, 9 and 10. In addition to the anomalous blow off, fuel stratification is observed to induce rough burning (Ref. 5). In order to show that anomalous blow off is possible under a stratified condition, gaseous propane was injected near the wall to produce a stratified condition. The mixture was allowed to be fuel rich near the step and fuel lean in the free stream in a vertical direction away from the step. The stratified condition was verified by means of a gas analyzer.

Figure 10 compares the blow off limits of both the stratified and homogeneous cases in a dump burner with a ½" step. Extremely small Ø values and a backward trend of the blow off limits were also observed in axisymmetric chambers (Refs. 9 and 10).

A cross-jet system is ideally suited under a condition where fuel stratification might prevail. First of all, the additional air from the jet would reduce the fuel rich state immediately ahead of the dump plane. Secondly, because of the amplified recirculation zone, the residence time of the fuel droplets would increase, thereby causing a more complete evaporation and mixing. In an extreme case, the cross-jets prevent rough burning caused by an excessively rich mixture in the vicinity of the step. Such an excessively rich mixture due to fuel stratification in a spray system has been reported (Ref. 10). Because of the lack of an adequate residence time the authors had suggested that fuel might be present in liquid phase in the recirculation zone immediately downstream of the step.

2.4. Pressure Loss

The loss of stagnation pressure is a major consideration for a propulsion system. Due to its geometric blockage, a bluff body flame holder is characterized by a relatively higher pressure loss than a dump combustor.

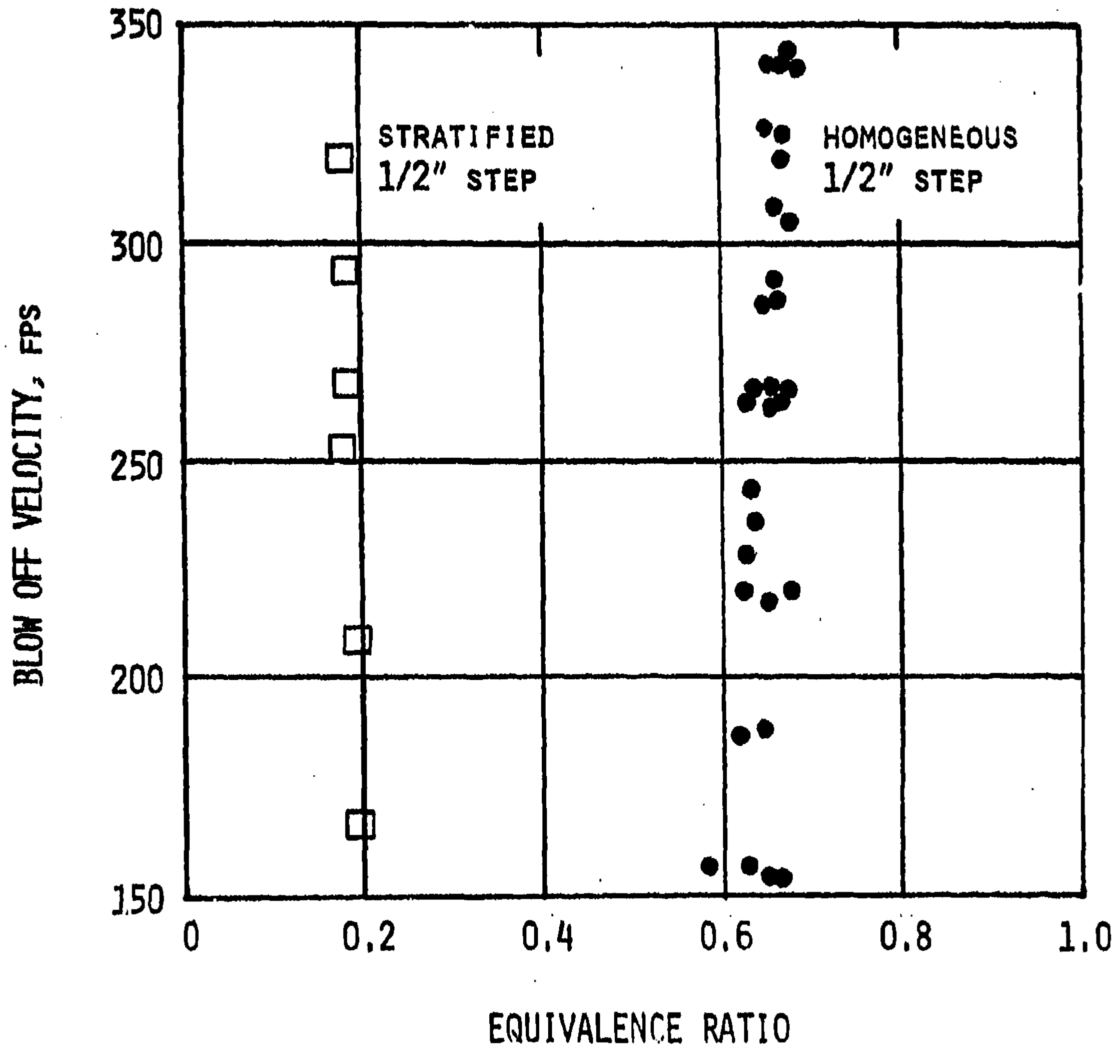


FIGURE 10 Effect of Fuel Stratification

Therefore, dump combustors have an inherent advantage over the present operational systems. However, when cross-jets are added and the flame spreading is dramatically increased, the drag penalty would also tend to increase. The stagnation pressure loss in a burner is directly proportional to the drag. A decrease in drag would allow a higher vehicle speed, lower fuel consumption and an increased range with a heavier payload.

In this section, the loss of stagnation pressure in different concepts are compared with that of a bluff body flame holder. The streamlined shape of the bluff body was selected on the basis of the shape of the flame plume. Several trial runs had to be made with different bluff body geometry to match the flame plumes shown earlier in Fig. 6. Figure 11 compares the loss of stagnation pressure for the jet system with that of a streamlined bluff body with the same flame spreading. The actual shape of the bluff body with 25% blockage is shown on the top of the figure. For reference, the stagnation pressure loss in a sudden expansion burner (inferior flame spreading) is also shown. The cross-jet system with discrete holes, including the bleed loss due to the axial momentum rate of the jet mass flow rate, has a lower stagnation pressure loss compared to the other systems with the same flame spreading. Since only one step and a single cross-jet system with 8 equally

spaced 0.042" holes were used, the losses shown in Fig. 11 will not apply when two steps with two jet systems are used. Figure 12 presents the stagnation pressure loss as a fraction of the upstream stagnation pressure relative to the streamlined bluff body. These values are not dependent upon the particular system chosen for the experiment. Figure 12 clearly shows the advantage of a cross-jet system. The pressure loss for the dump burner is very low. However, the flame spreading in such a system in marginal.

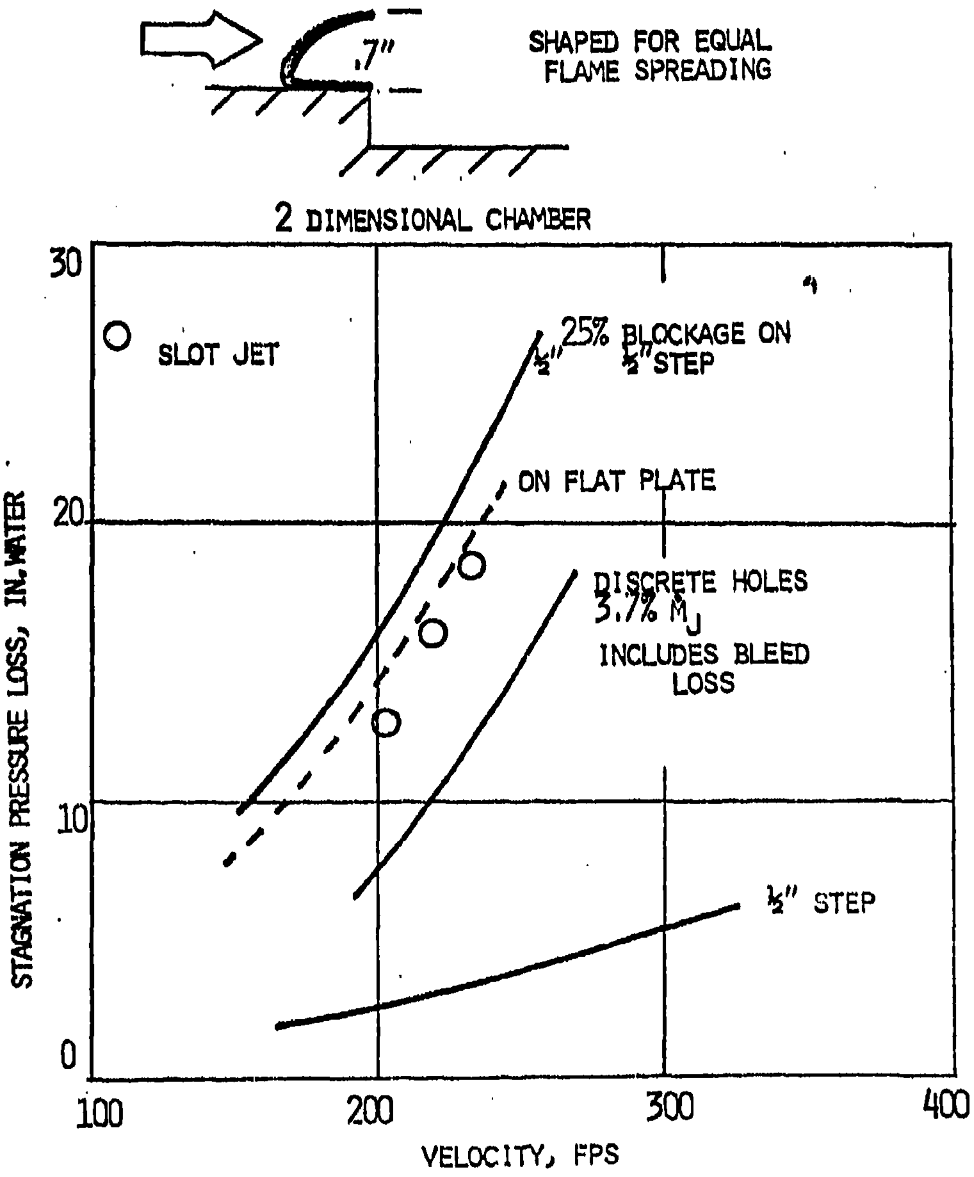


FIGURE 11 Stagnation Pressure Loss for Various Systems

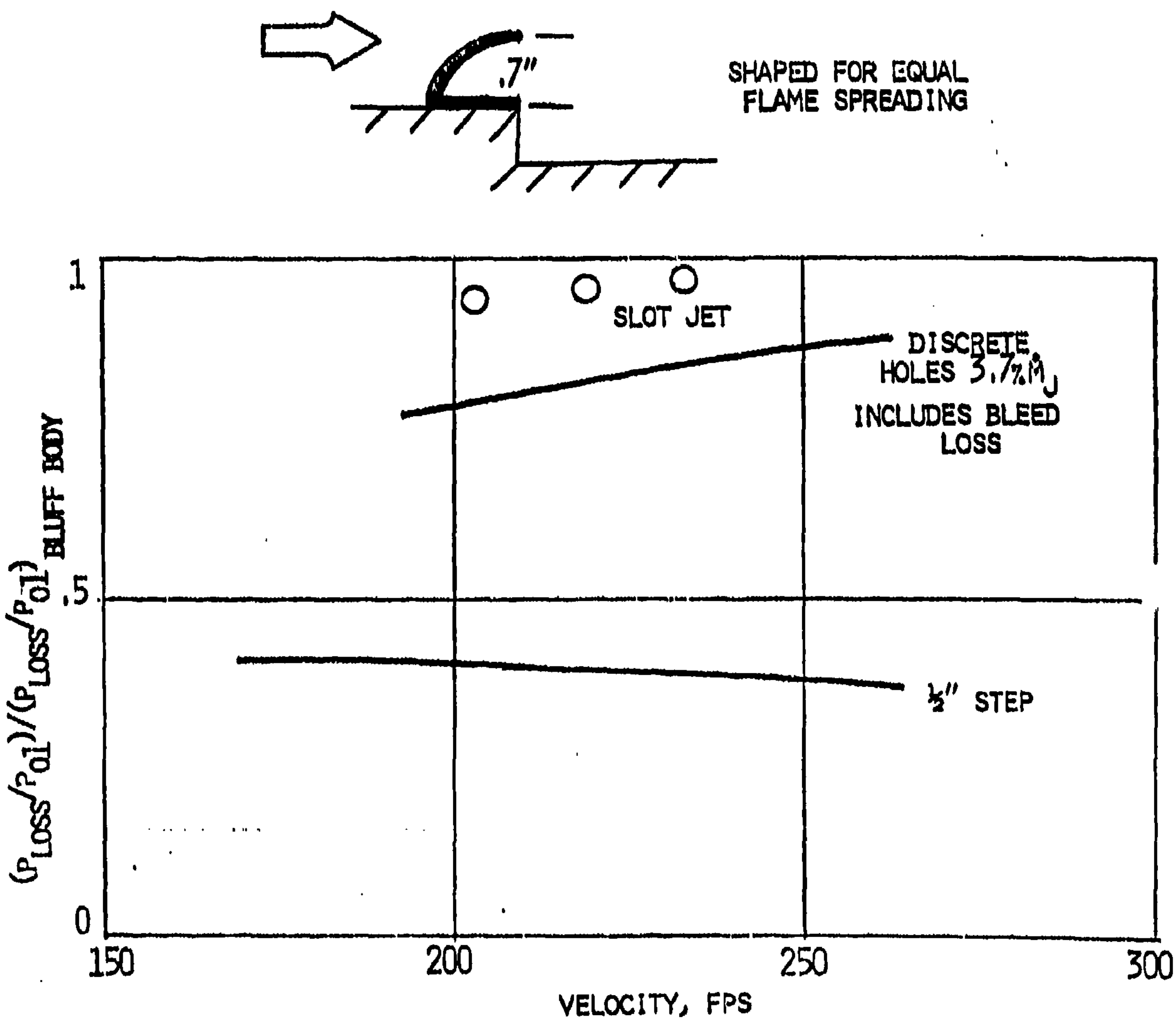


FIGURE 12 Fraction of Bluff Body Pressure Loss
(p_{o_1} = upstream stagnation pressure)

III ROUGH BURNING

3.1. Chamber Pressure Fluctuations

Rough burning in a volume limited two dimensional dump burner can occur either due to the nozzle location or due to locally rich combustible mixture (Ref. 5). This Chapter is devoted to the study of rough burning, the parameters which are responsible for it and possibilities of promoting smoother burning. Most of the experiments were conducted in the 3" x 1" channel burner. Movable ramps of various thicknesses (Fig. 3) simulated the nozzle whose location was easily adjusted to obtain L/h values between 1.0 and ∞ (L = distance to the ramp and h = step height.) The thickness of the ramp can also be changed to vary the nozzle to chamber area ratio A_n/A_c from 1.0 to about 0.8. A microphone located on the upper wall (Fig. 3) was used to obtain pressure fluctuations in the chamber.

Pressure traces at two different chart speeds (25mm/sec and 125 mm/sec) were obtained for both cold and reacting flows with different values of L/h. Figure 13 shows typical pressure traces in cold flow when the position of the nozzle is changed at a constant free stream velocity of 290 fps. Under cold flow condition, neither the nozzle location nor the free stream velocity up to 400 fps had any effect upon

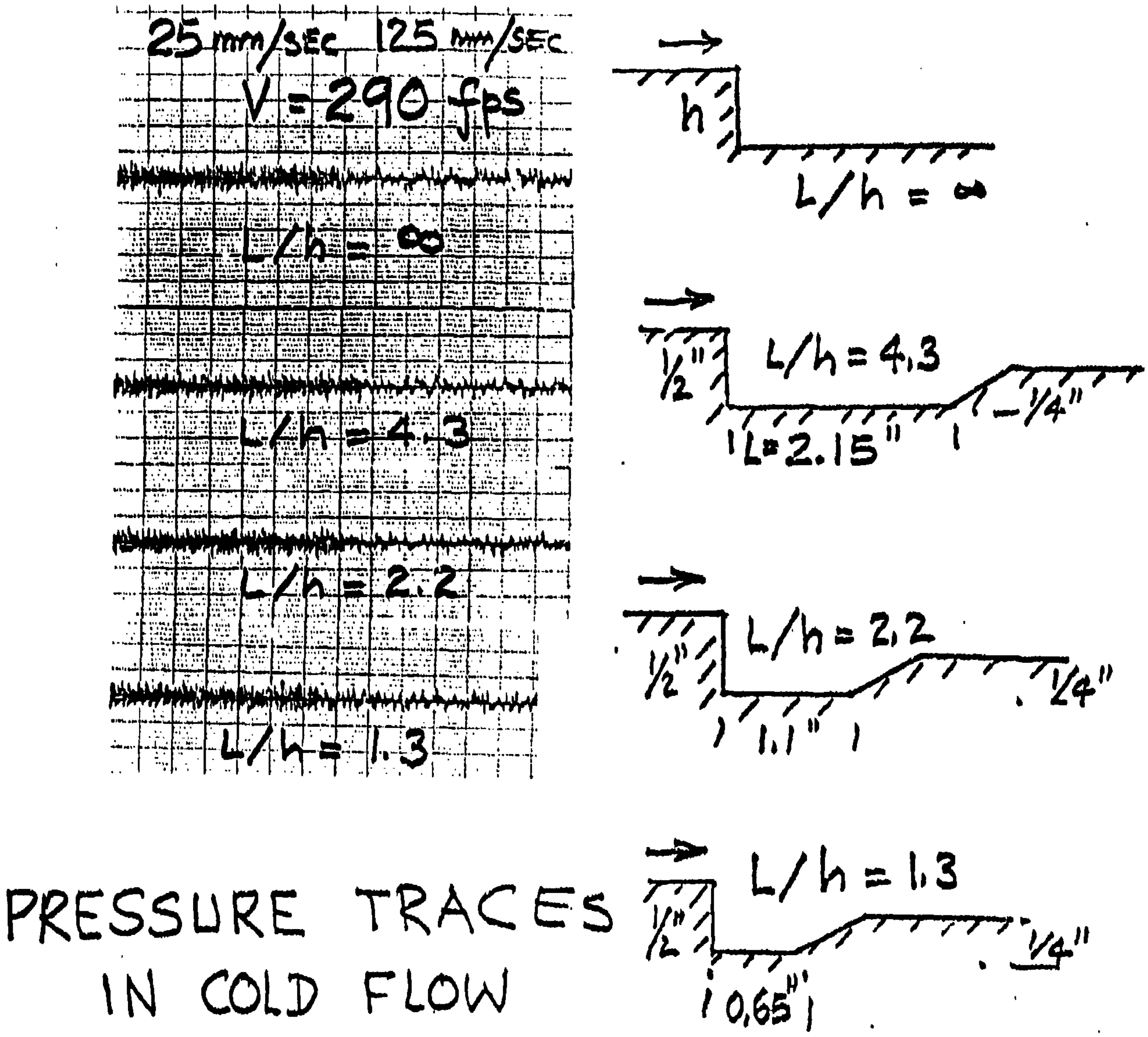
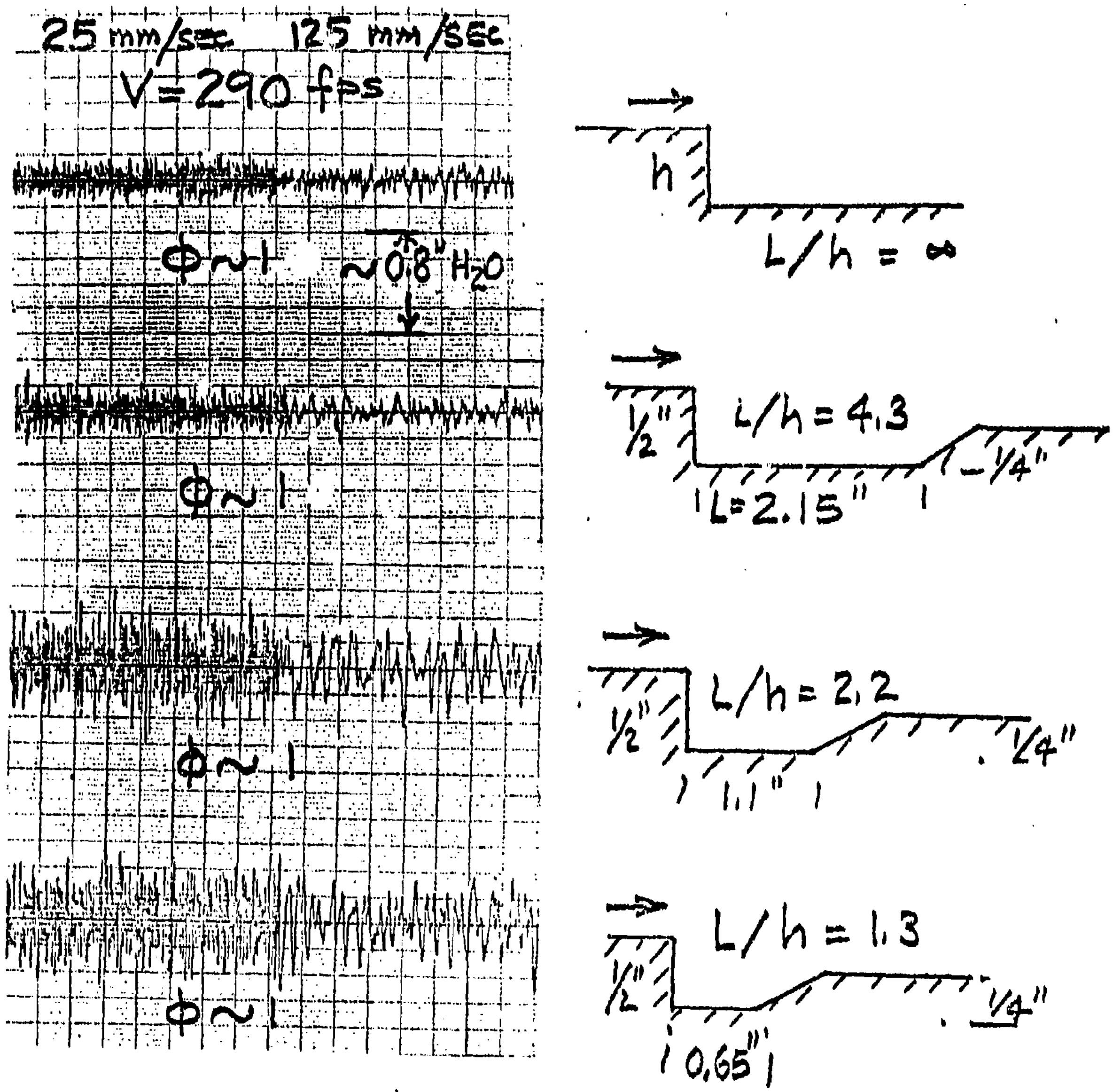


FIGURE 13 Cold Flow Pressure Traces at 290 fps for Various L/h Ratios and Two Chart Speeds

the chamber pressure fluctuations. Even though large pressure fluctuations and noise at discrete frequencies are possible in cavity flows (Reference 11), the present range of velocities is too low for such a situation to occur. With burning, however, large fluctuations in chamber pressure are observed particularly at smaller values of L/h when the nozzle is brought closer to the sudden expansion step. Pressure traces for different L/h ratios with roughly a stoichiometric mixture of propane and air are shown in Figure 14.

Figure 15 shows the effect of both the slot and cross-jet systems on the pressure fluctuations. An equivalence ratio of about 1.4, close to the rich blow off point, was chosen to provide a maximum roughness in burning. Such a rich mixture might occur locally when the fuel becomes stratified due to incomplete evaporation in a burner with a small characteristic length. Thus, both geometric constraint and rich mixture are responsible for inducing roughness shown in Fig. 15. Both the slot-jet and jet system with discrete holes are seen to be equally effective in reducing the pressure fluctuations. If the amplitude of pressure traces is considered as an index of rough burning, both jet systems are equally capable of smoothing out rough burning in a compact, volume-limited dump burner. Rough burning is evidenced not only by the pressure traces but



ROUGH BURNING DUE TO NOZZLE LOCATION; V= 290 fps; $\phi \sim 1$

FIGURE 14 Pressure Traces at $\phi \sim 1$, 290 fps, and Two Chart Speeds

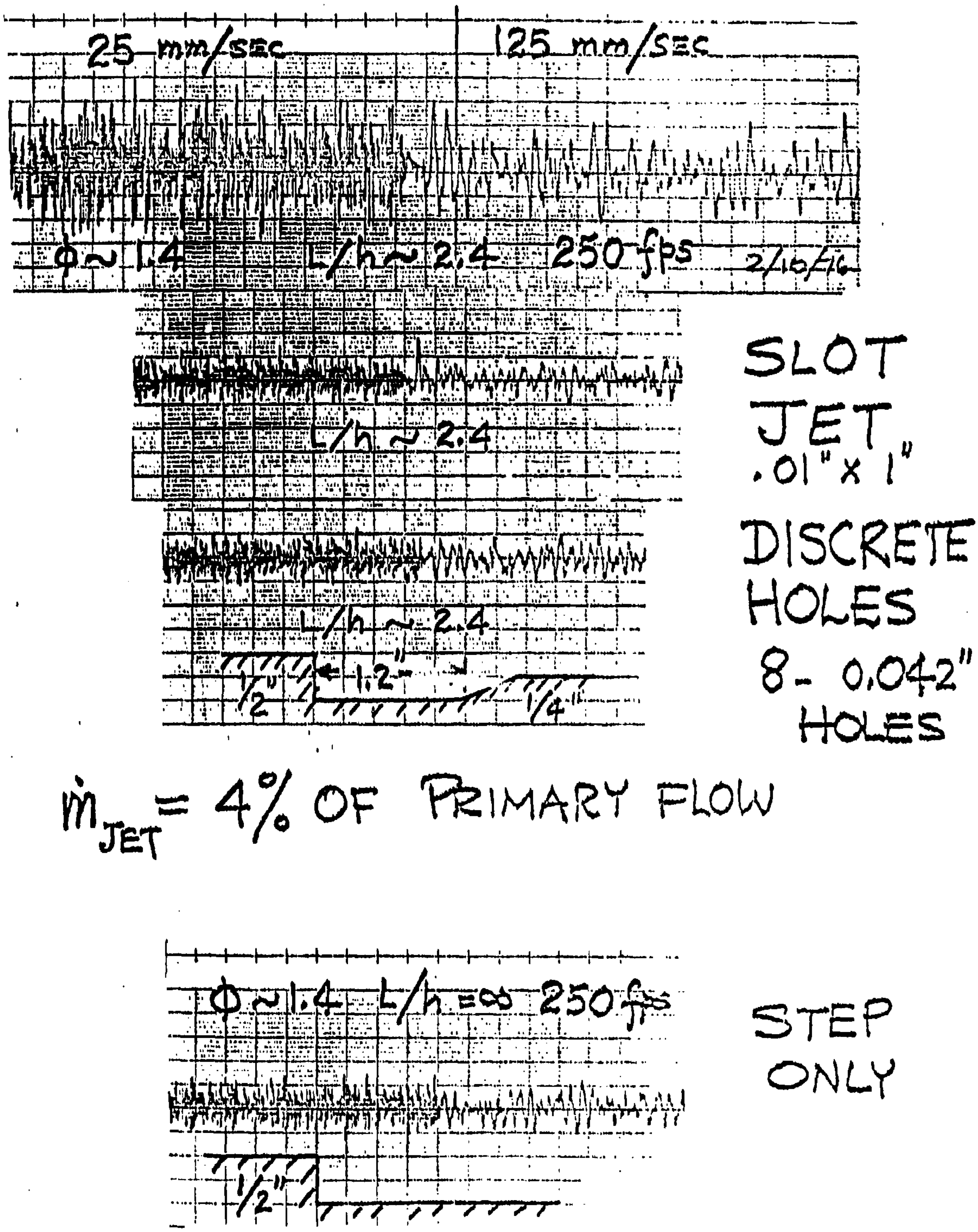


FIGURE 15 Smoothing Effectiveness of Jet Systems

also form visual observation of the flame and the noise emitted from the burner.

A study of the pressure traces show that for a given step height, the amplitude depends upon the values of L/h, velocity, equivalence ratio and the nozzle to chamber area ratio, A_n/A_c. Larger values of L/h, lower velocity, equivalence ratios away from blow off and $A_n/A_c \to 1$ help eliminate large pressure amplitudes. Even though most of the experiments were performed in the channel burner, preliminary observation indicates that these general trends can also be expected in a small 3" diameter axisymmetric burner.

3.2. Spectral Character of the Intensity of Pressure Fluctuations

From the broad band (roughly 1 octave) data of the intensity level of pressure fluctuations the calculated spectral levels for cold flow conditions are shown in Figure 16. The details of the instrumentation appear in Reference 12. In cold flow the spectral intensity levels are independent of both the free stream velocity U_o and L/h. This is consistent with the cold flow pressure traces which were also independent of these two parameters. Figure 17 is a comparison of the spectral intensity levels of the cold and hot flows for L/h = 2.2, $\emptyset \sim 1$ and U_o = 235 fps. Figure 17 is typical of rough burning in the

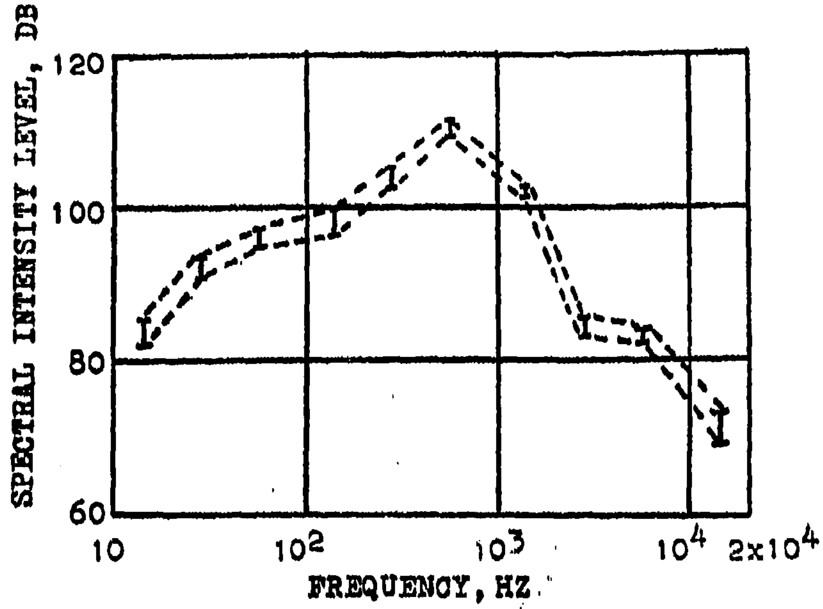


FIGURE 16 Spectral Intensity Level of Pressure Fluctuations Cold Flow. L/h = 2.2 to ∞. U_o = 235 to 330 fps

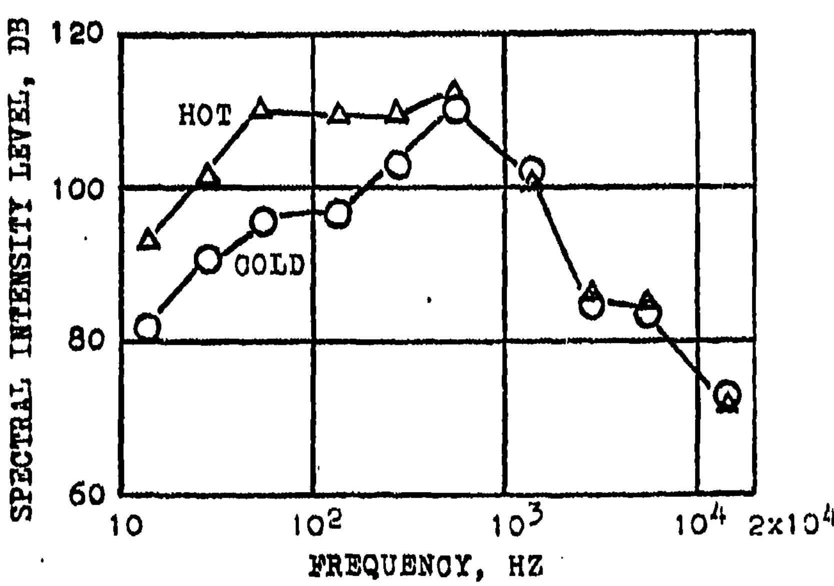


FIGURE 17 Spectral Intensity Levels for Cold and Hot Flows. $\phi \sim 1$, L/h = 2.2, U_o = 235 fps

same sense that the increase in the spectral level due to roughness is only over a low frequency range (10 to 300 hz approximately.) In general, these low frequencies are very often associated with the pressure fluctuations in the feed lines. However, in the present system, changes in the damping of the feed line did not eliminate the frequency characteristics of the intensity level of pressure fluctuations. The spectral intensity levels of Figs. 16 and 17 are calculated from broad band data. Thus, the curves are relatively smooth and do not show the actual intensity of fluctuations over a very narrow band width. Rapid, large fluctuations between 20 to 400 hz and smaller ones between 400-800 hz are observed on the noise level meter. At other frequency ranges there were no perceptible fluctuations.

Since low frequencies correspond to large characteristic times, the spectral distribution of intensity level suggests that the mechanism of roughness is controlled by fluid mechanics and heat transfer. For a fast reacting system of stoichiometric mixture of propane and air the characteristic reaction time is rather small. Therefore, if the rough burning was kinetics controlled, the increase in spectral intensity level would occur at a much higher frequency (on the order of 10^3 hz). Hence it is evident that the rough burning is controlled by fluid mechanics

and heat transfer and not chemical kinetics. A coupling with chemical kinetics at these low frequencies would occur only for a combustible mixture with a small characteristic reaction time. This observation is of great significance in analytical modeling of compact dump combustors of small characteristic length. If the chemical kinetics is uncoupled from the analysis, the resulting equations in comparison, are relatively less complicated. This is particularly true for burners using hydrocarbon air mixture or other combustibles with fast reaction times.

3.3. Probable Causes of Rough Burning

Visual observation of the phenomenon of rough burning suggests that the instability of the shear layer emanating from the edge of the sudden expansion step causes pressure fluctuations in the chamber. The process of heat addition to the shear layer seems to induce certain instability in the form of flip-flop motion as portrayed in Figure 18. In cold flow, within the range of velocities investigated, no such motion was evident. Only the hot flow produced such a low frequency motion. The range of frequencies was low enough to intermittently observe the pulsation of the burning shear layer which alternately strengthens and weakens the recirculation zone. It is felt that the periodic perturbation of the recirculation zone is largely

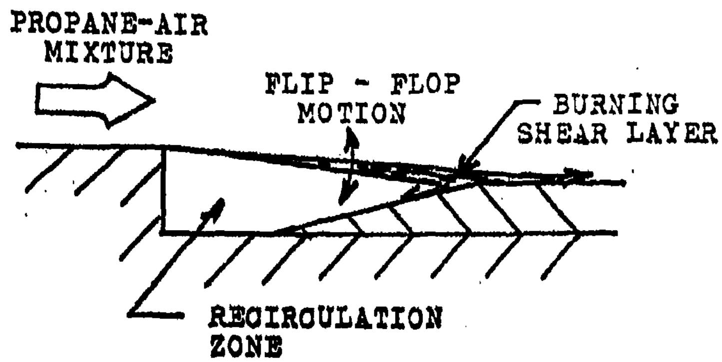


FIGURE 18 Unstable Flip-flop Motion of the Shear Layer

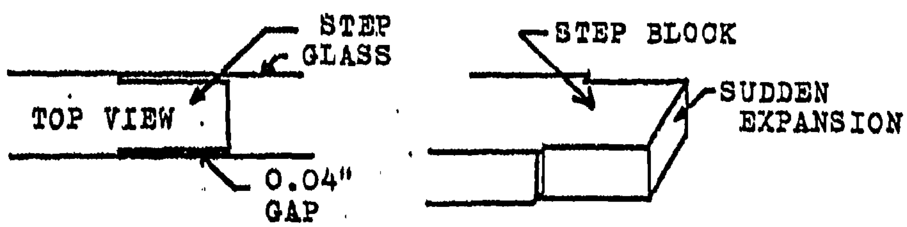


FIGURE 19 Slots for Changing the Shear Layer Characteristics at the Step

responsible for the pressure fluctuations shown in Figure 14. For the case of a combustor with a small value of L/h the shear layer impinges on the lip of the nozzle and the propagation of the flame sheet is alternately obstructed by the lip. This phenomenon can be observed by means of a moderately high speed (64 frames per sec., for example) motion picture.

In order to check out the validity of this observation, 0.04" slots were cut on the sides of the step block. These slots, shown in Figure 19, are similar in dimension to the gaps for gaskets between the step block and the glass window. The presence of these gaps alters the characteristics of the shear layer at the step and perhaps delays the onset of the instability which perturbs the recirculation zone. Figure 20 shows the pressure traces with the 0.04" slots on both sides. Slots of other sizes, for example, are also able to smooth out roughness caused by the instability of the shear layer. Other schemes, such as for example, small protruberances at selected upstream locations, can be utilized to produce similar effect on the pressure fluctuations. However, the flame spreading is still marginal with this method of smoothing out roughness. As indicated earlier, the jet system not only smooths out roughness but also increases the size of the recirculation zone. Thus, both the shear layer characteristics and the

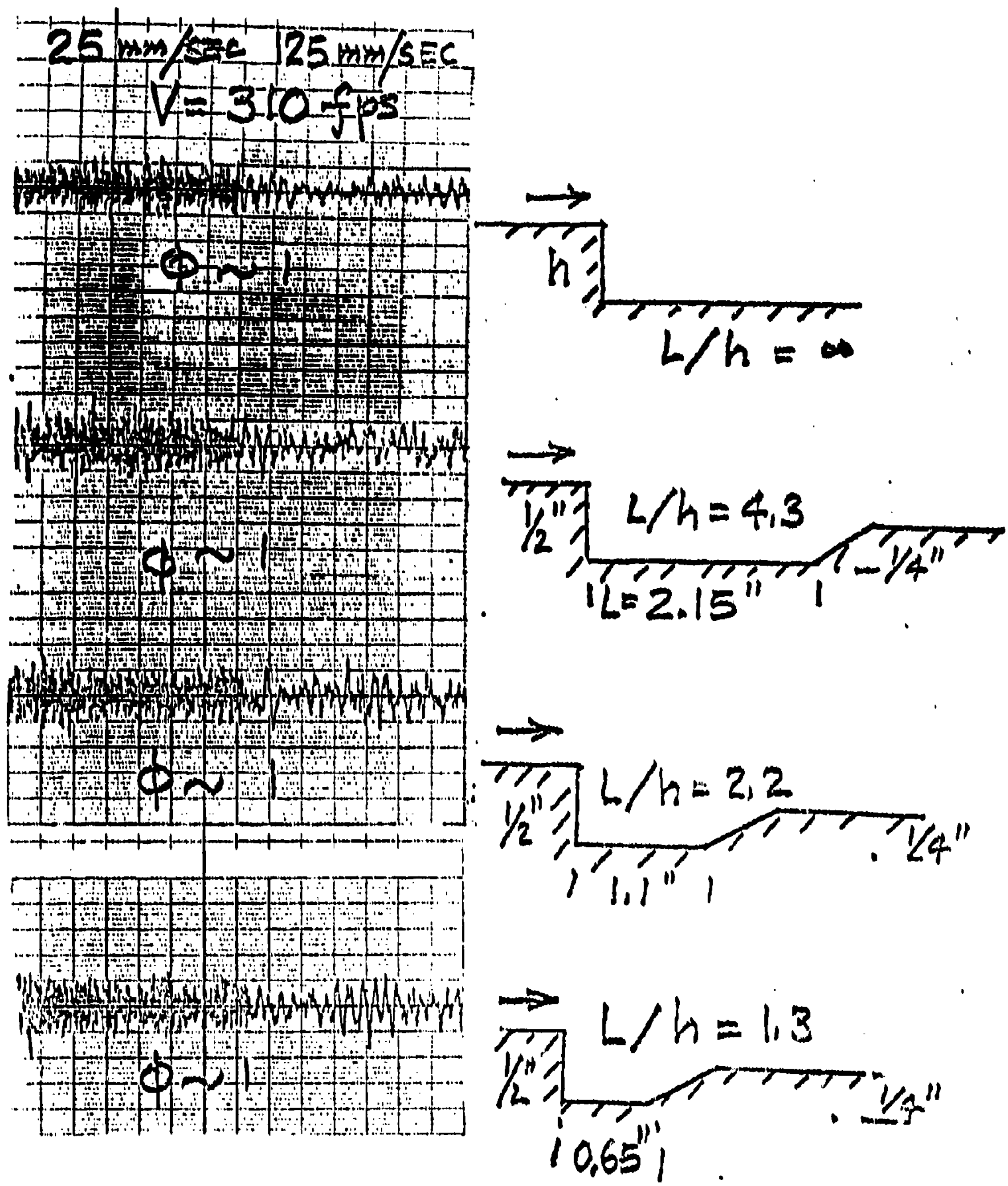


FIGURE 20 Smoothing Effectiveness of .04" Slots
U_o = 310 fps, $\phi \sim 1$

recirculation zone downstream of the step are changed simultaneously. With the cross-jets the nozzle downstream of the step is literally "swallowed" up by the newly created recirculation zone. As a consequence, the roughness disappears and the burner performance is independent of the geometric influence downstream of the step.

Even though most of the investigations of this chapter were carried out primarily in a two dimensional channel burner a preliminary study of an axisymmetric burner with a sliding rear ramp of variable thickness also showed basically the same trend.

AMPLIFICATION OF RECIRCULATION ZONE BY MEANS OF CROSS-JETS

4.1. Cold Flow System - Experimental Apparatus

Cold flow studies have shown earlier that the cross-jet system acts as a fluid amplifier and significantly amplifies the size of the recirculation zone. This observation is indirectly substantiated by the fact that both cross-jet systems are able to smooth out rough burning in a small volume-limited combustion chamber. All the observations so far had been qualitative in nature. Experiments in cold flow are described in this chapter to quantitatively define the degree of amplification of the recirculation zone.

A 2" x 1.5" channel with a series of 0.02" static pressure holes (¼" apart) both upstream and downstream of the sudden expansion step were used to measure the local static pressure. There were two static pressure holes on the upstream side, one on the face and a total of 18 downstream of the step. A 0.02" i.d. total pressure probe along with the local static pressure was used for determining the local axial velocity in the chamber.

In addition to the flat plate configuration step heights of 1/8", 1/4" and 1/2" were used. The cross-jet

system consisted of 8 equally spaced 0.05" diameter holes located 1/8" upstream of the step. Only one cross-jet system was investigated in detail.

A 0.0001", 10% Rhodium-Platinum constant temperature hot wire anemometer system was used to provide a cross check on the pitot tube data. Since the flow field is highly trubulent and possibly three dimensional in the separated region it is very difficult of obtain true values of axial velocity and its fluctuations. This is partiacularly true in the recirculation region where the axial velocity is nearly zero.

4.2. Pressure Distribution and Zero Axial Velocity Zone

Figure 21 shows the distribution of pressure coefficient c_p in the chamber with and without the cross-jet system. With a value of $\dot{m}_j/\dot{m}_a = 0.03$*, the figure clearly shows the increased distrurbance introduced in the flow field by the cross-jet system.

In order to determine the effect of the cross-jet system on the overall flow field downstream of the step, the approximate locii of the zero axial velocity were obtained in cold flow. This was done by moving the total pressure probe down from the free stream until the

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* The mass flux ratio for this configuration is 3.54.

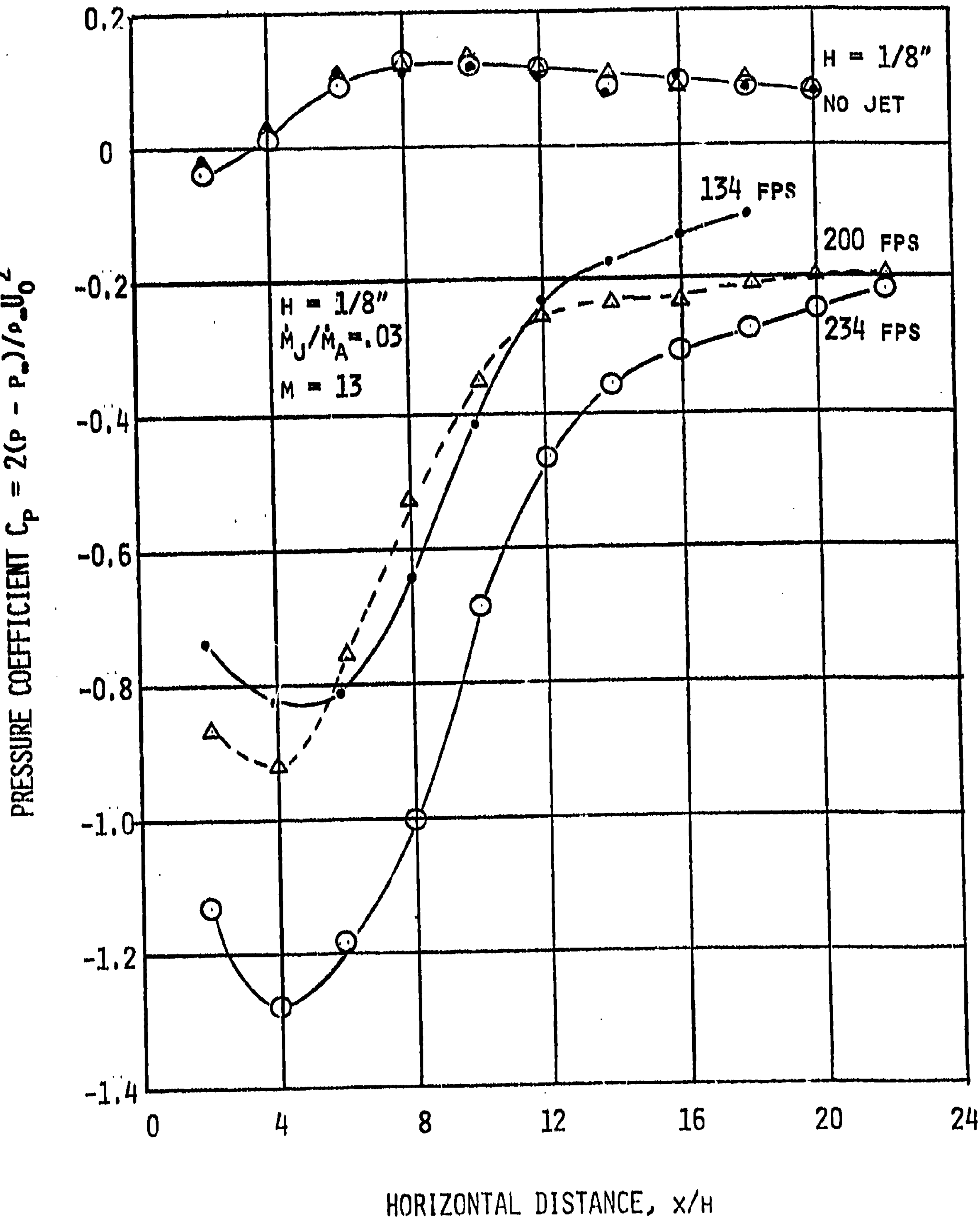

FIGURE 21 Pressure Distribution in a Channel Burner. Cold Flow (M = momentum flux ratio)

difference between the local wall static and the total pressure vanished. The inherent uncertainty of this technique near the null point is reflected in the data scatter of Figure 22. To provide a cross check for the zero axial velocity zone, the velocity distribution was extrapolated to define the region of zero velocity. Both methods resulted in approxiamtely the same boundaries of zero axial velocity zone. It was also found that the boundary of the zero velocity zone represents the maximum rms output of the hot wire. Figure 23 compares the pitot tube results with those of the hot wire measurements. Even though the hot wire probe was mounted in such a way that the signal was supposed to be proportional to the axial component of the velocity, the maximum e_{rms} shown is Figure 23 is not actually the rms signal due to the axial velocity. Near the null point, the fluctuations in x, y and z directions are similar in magnitude. Disregarding the component along the length of the wire, the e_{rms} value perhaps corresponds to both the x (axial) and z components of the velocity fluctuations. Since the objective is to compare the degree of magnification of the recirculation zone, no attempt was made to isolate and solve for each of these fluctuating components by using a cross wire.

The data points shown in Fig. 23 are averaged data

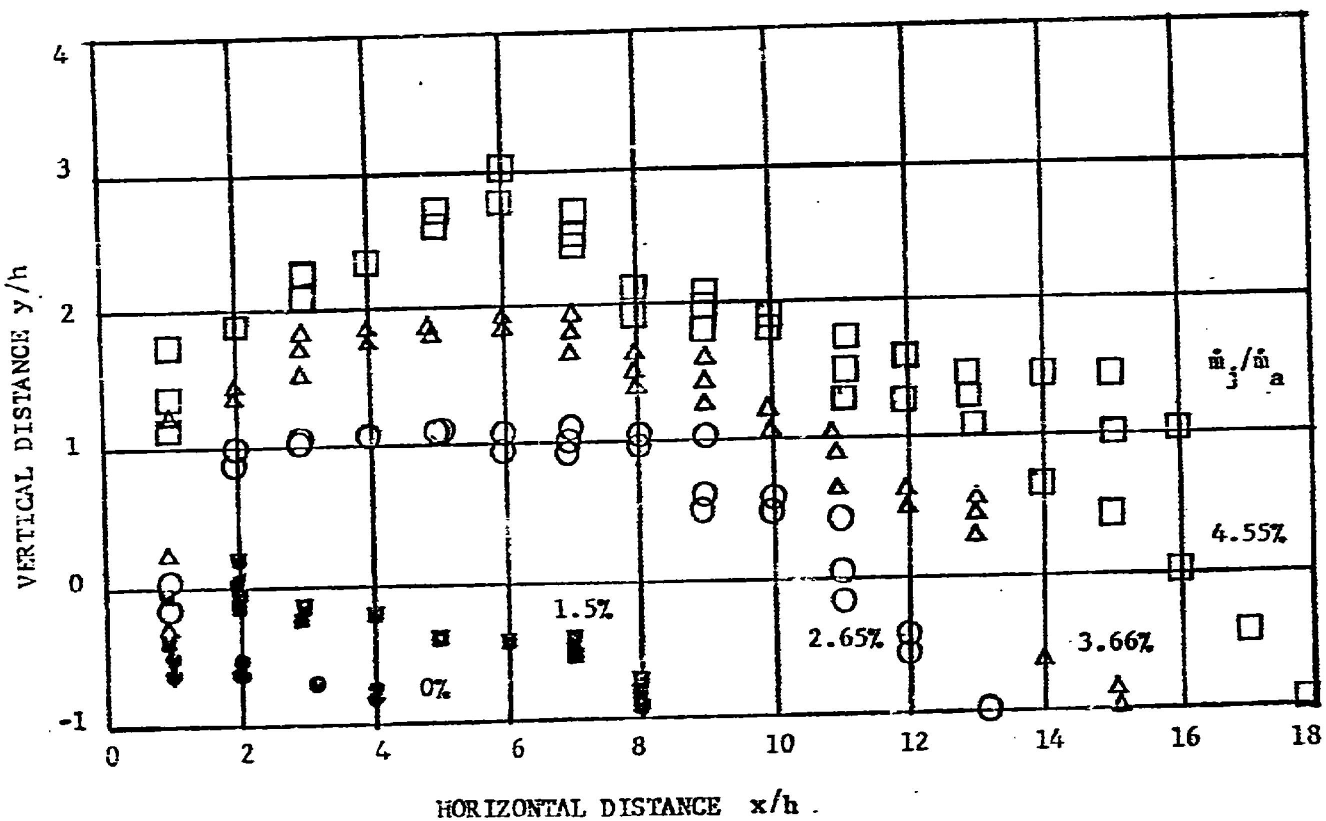

FIGURE 22 Typical Zero Axial Velocity Zones for Different Jet Mass Flow Rates. 1/4" Step, U_o = 134 fps

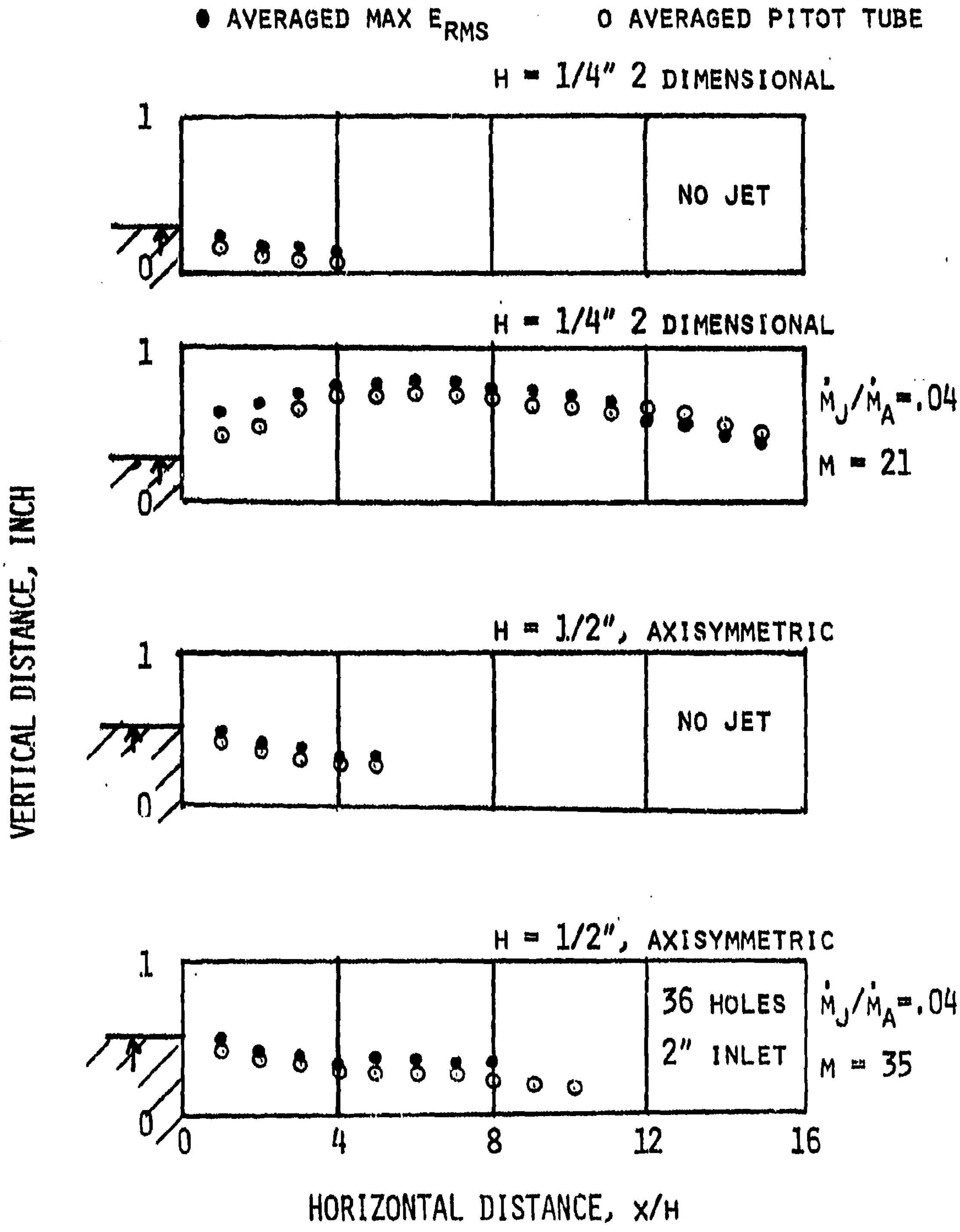

FIGURE 23 Comparison of Zero Axial Velocity Zone and maximum e_{rms} signal of a hot wire

points at a given location. Therefore, the data scatter shown in Fig. 22 does not appear in Fig. 23. It is necessary to emphasize that the zero axial velocity zone is within the recirculation velume and is smaller than the recirculation zone. However, it is reasonable to assume that an amplification of the zero velocity zone would cause a corresponding increase in the size of the recirculation zone. Therefore, the overall effect of the jet even with a very low mass flow rate is to increase the residence time and completely alter the shape and the character of the streamlines in the immediate vicinity of the cross-jets.

With burning, the details of the flow field shown in Figs. 22 and 23 are expected to change. However, the overall picture of how the jet flow influences the entire flow field and helps smooth out rough burning can be ascertained from the cold flow studies. The influence of the jet system, in cold flow, is so strong that sizeable recirculation zone can be established easily even on a smooth flat plate. Figure 24 shows the zero axial velocity zones on a flat plate without any step. In order to eliminate undue clutter in the figure, the actual data points are not shown and smooth lines are drawn through the points. As before, a survey of the static pressure in the vertical direction showed only a small change from the local wall pressures beyond about 1/4" downstream of the jet system. Static pressure variation in the vertical

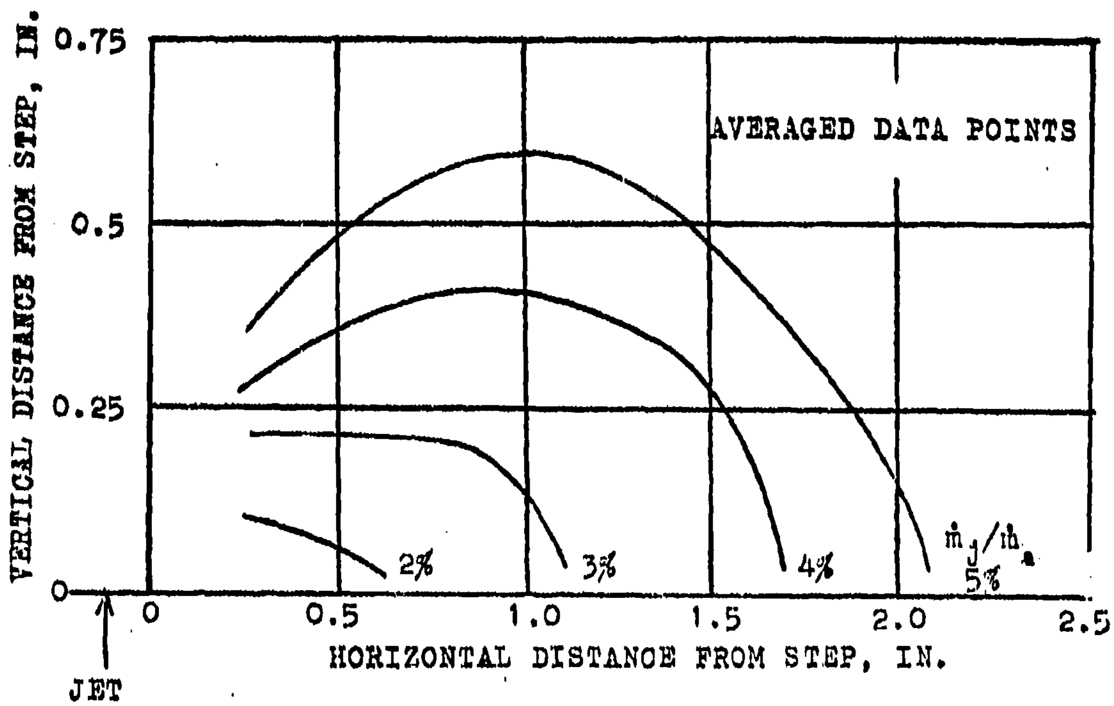

FIGURE 24 Zero Axial Velocity Zones on a Flat Plate. U_0 = 134 fps

direction was ignored and the zero axial velocity zones were determined by using the local wall static pressure.

The large size of the zero axial velocity zone (i.e., the recirculation zone) even with a low mass flow rate is responsible for flame stabilization on a flat plate by means of a slot-jet (Fig. 8). In cold flow the maximum penetration of the zero axial velocity zone in the vertical direction is independent of the step size downstream of the jet. The maximum penetration y_{max} scales with either the ratio of jet to primary mass flow rates or the momentum fluxes. The maximum size of this zone in the axial direction x_{max}, on the other hand, depends upon both the step size h and $\dot{m}_j/\dot{m}_a$ (or the mom. flux ratio). Figure 25 is a plot of y_{max} vs $\dot{m}_j/\dot{m}_a$ for a variety of cases. Figure 26 is a plot of x_{max}/h vs $\dot{m}_j/\dot{m}_a$. Even though both y_{max} and x_{max}/h increase rapidly with the mass flux ratio, too much jet air can be detrimental and rough burning sets in. For optimum operation, a mass flux ratio between 3 and 11 is adequate. By modulating the jet flow rate within this range, one can effectively control the flame spreading, the size of the recirculation zone (i.e., the residence time), rough burning and mixture stratification. These effects can be further intensified as the need arises, by changing the cold jet air to heated air or combustible mixture.

Both slot-jet and a system of cross-jets can be used effectively to make a compact, volume-limited burner with

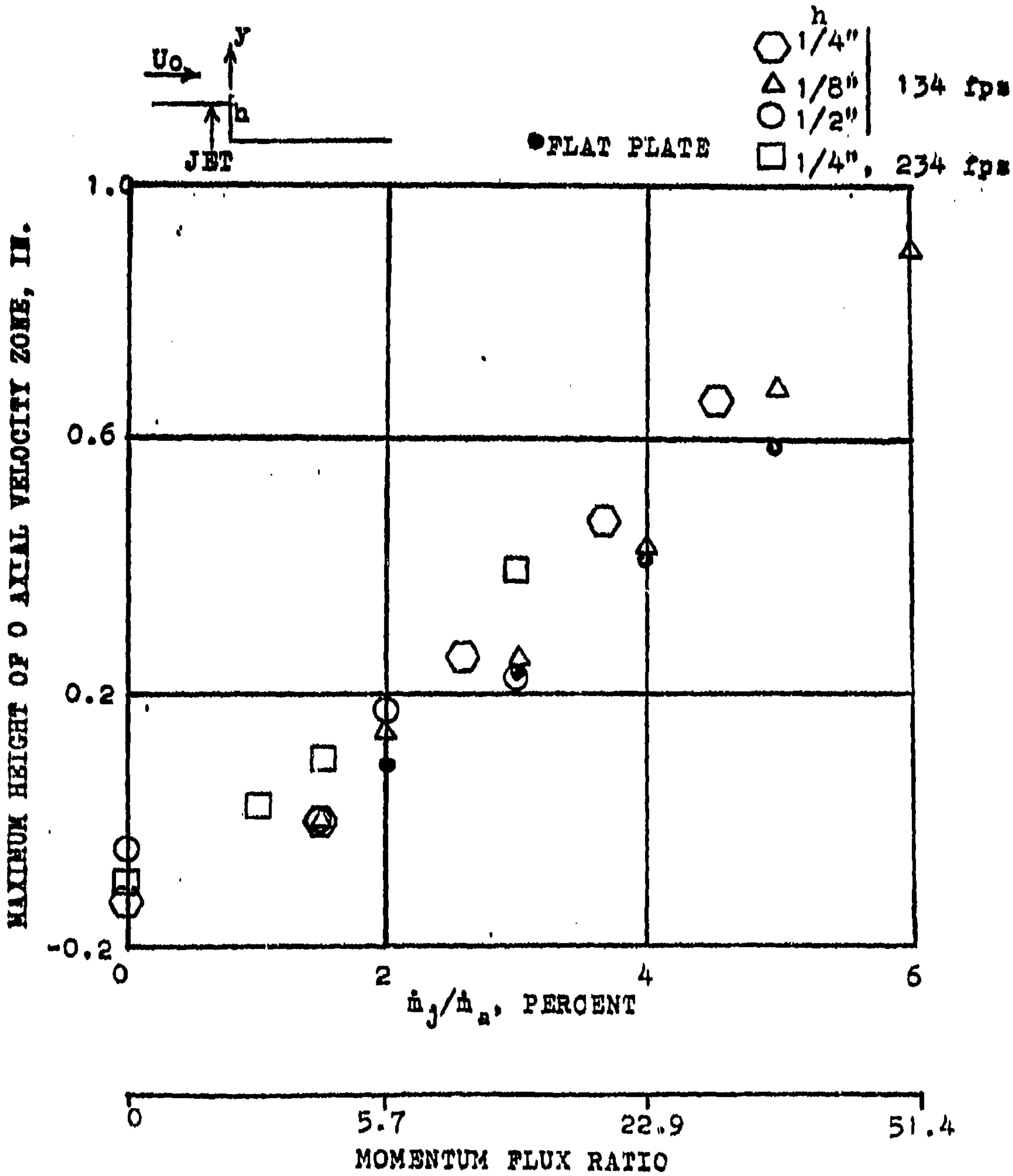

FIGURE 25 Maximum Vertical Penetration of Zero Axial Velocity Zones

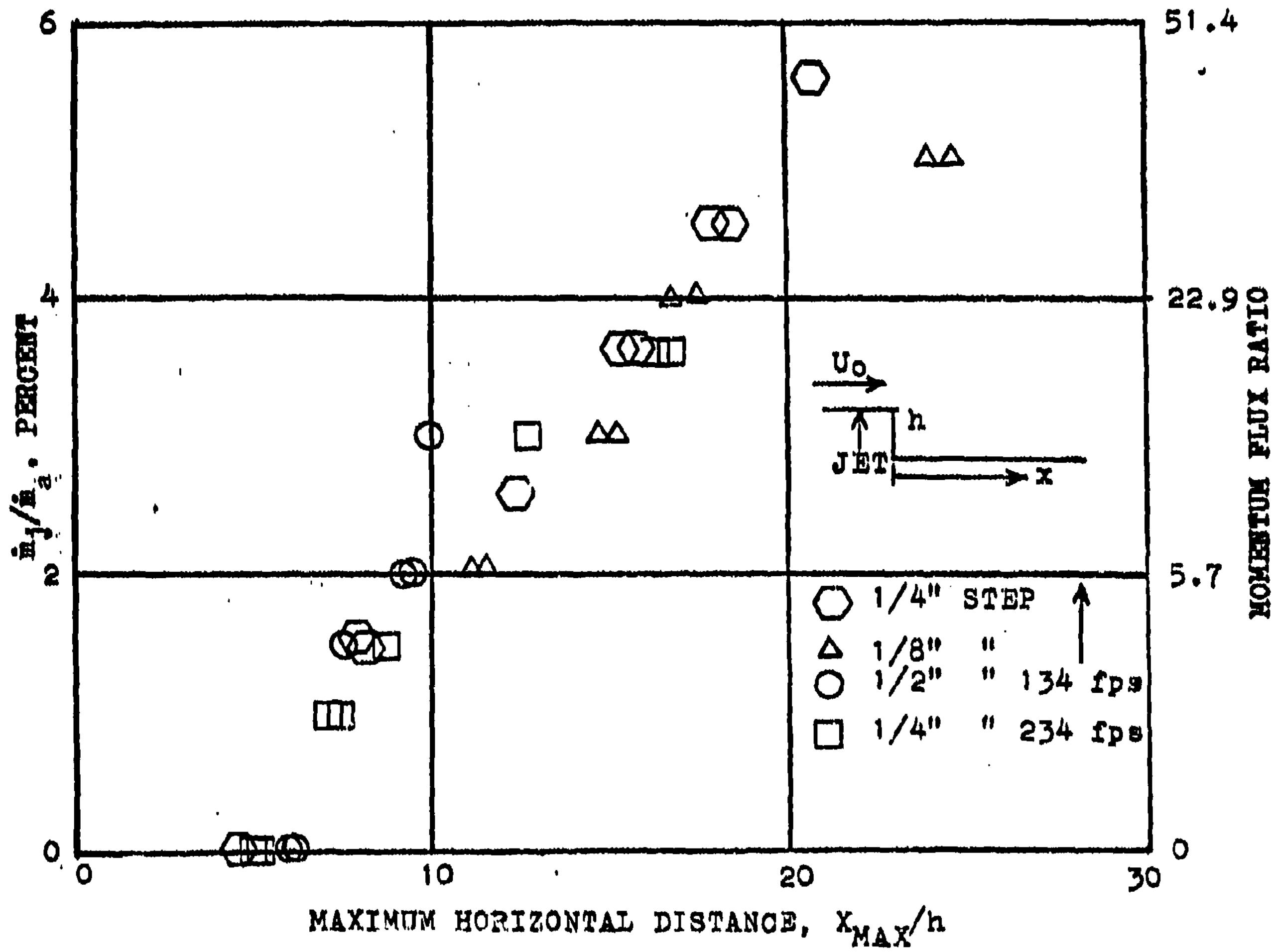

FIGURE 26 Maximum Horizontal Penetration of the Zero Axial Velocity Zones

a smooth burning characteristics. However, the cross-jet system with discrete holes is preferable because of the ease of construction and lower pressure drop. In addition, with the system of cross-jets, the burner performance is not as sensitive to sudden small changes in flow parameters as with the slot-jet.

4.3. Distribution of Turbulent Intensity

The influence of the cross-jet system on the entire flow field can be appreciated by comparing the distributions of turbulent intensity with and without the jet. Figure 27 is a plot of V_{rms}/U_o at various locations in a rectangular chamber with only a sudden expansion step. The value of V_{rms} corresponds to the hot wire output e_{rms}. It probably represents the velocity fluctuations both in the x (axial) and z directions. It is, however, normalized by the free stream velocity U_o upstream of the step. Figure 28 is a similar plot with a jet mass flow rate of 4% of the primary stream (mass flux ratio of 4.7). A comparison of these two figures show the effect of the jet and how the disturbance persists far downstream.

Similar experiments have been performed on an axisymmetric chamber with a 2" diameter inlet. The cross-jet system in these experiments consisted of 36 1/32" diameter holes located at a distance of 5/8" upstream of the sudden expansion step. Unfortunately, because of the small inlet

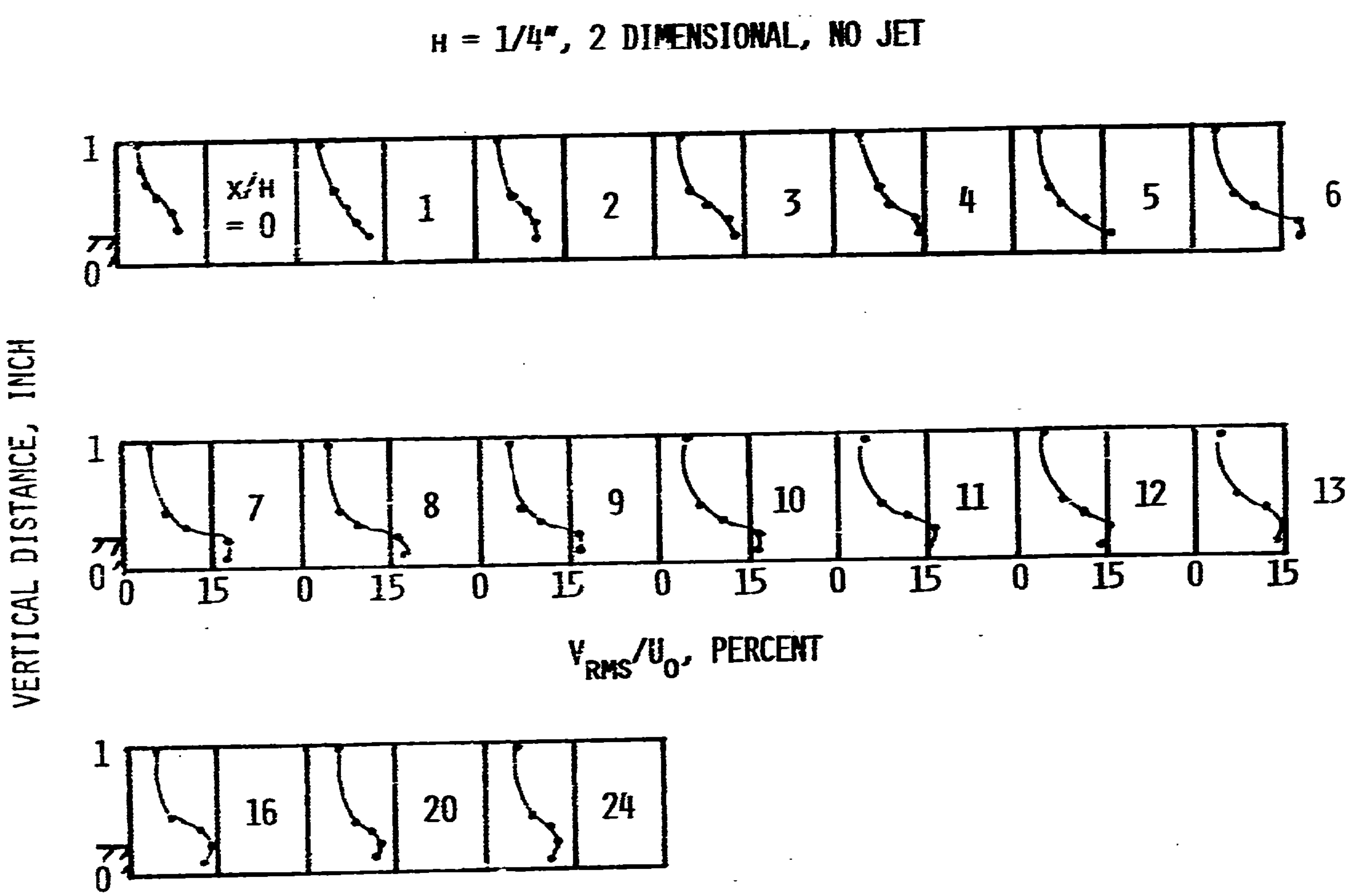

FIGURE 27 Turbulent Intensity Distribution in a Channel Burner. Cold Flow

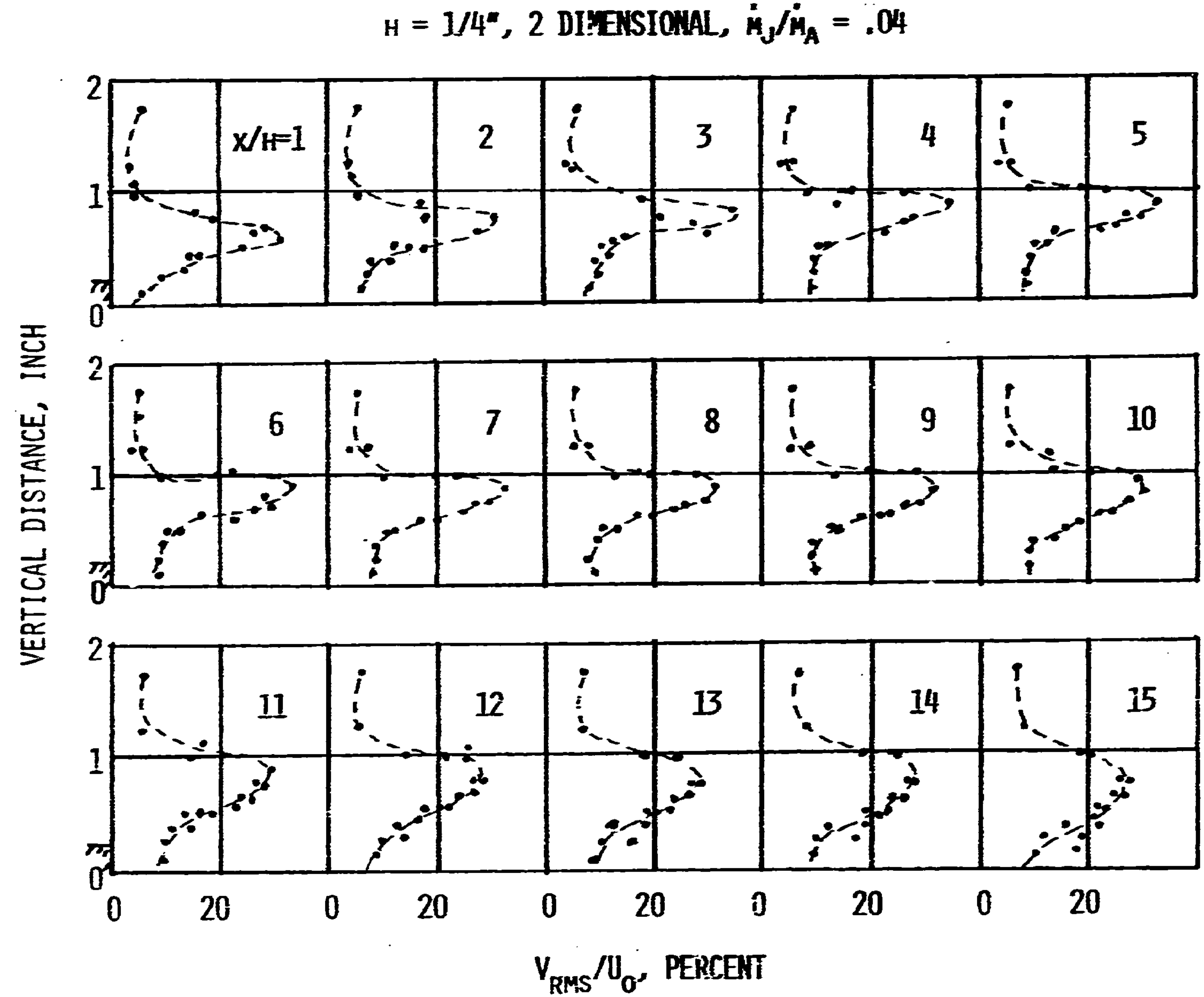

FIGURE 28 Turbulent Intensity Distribution in a Channer Burner with Cross-jets. Cold Flow.

diameter, interference between jets caused only a slight amplification of the recirculation zone. However, when the top half of the system (18 holes) was blocked off, a substantial increase in the size of the recirculation zone was observed. Figure 29 shows the zero axial velocity zones for a number of cases. The results show the importance of the jets in geometric scaling, i.e., in a small chamber the interference between jets can completely negate their beneficial effects. A chamber of large radius is expected to behave in a manner similar to the two dimensional system with jets.

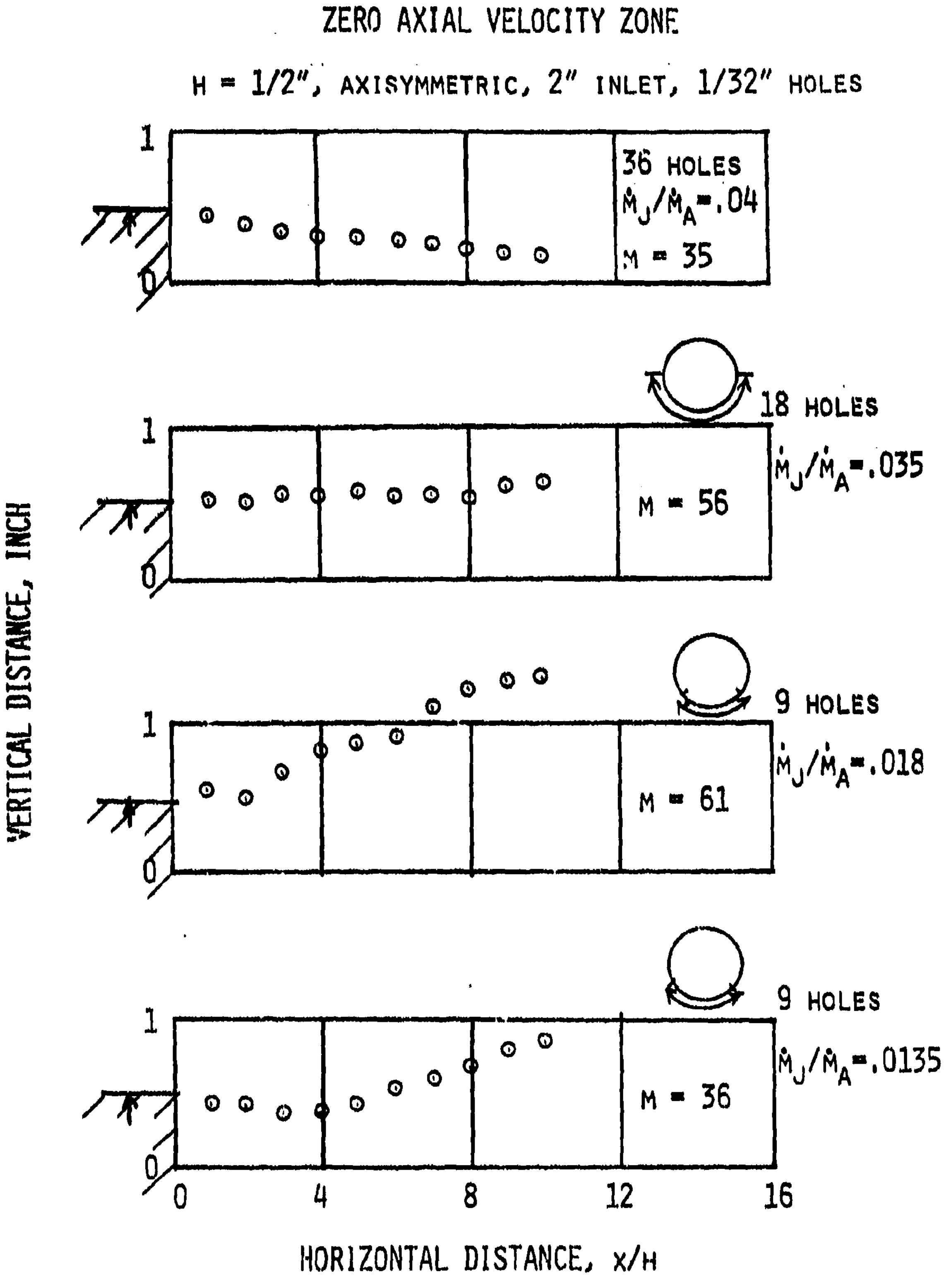

FIGURE 29 Effect of Jet Interference on the Recirculation Zone Size. Cold Flow (M = momentum blux ratio)

V. OTHER BURNERS AND GEOMETRIC SCALING

5.1. A 3" Diameter Cylindrical Burner

This particular burner had an inlet diameter of 2". It had a 1/2" step and 36" jet holes located 1/2", 5/8" and 3/4" upstream of the step. Jet diameters, depending upon the configuration, range from 0.032" to 0.05". The choice of a 1/2" step was dictated by previous experiments with different step sizes. Lean flame blow off limits of the axisymmetric burners are compared with those of the channel burners in Figure 30. The two dimensional system appears to have a slightly higher equivalence ratio at blow off possibly due to larger rate of heat transfer caused by a relatively small flame spreading into a large chamber. In the axisymmetric chamber it is possible to shift the equivalence ratio at lean blow off by means of controlling the heat transfer rate. For example, because of an increase heat transfer the equivalence ratios at blow off in a cooled aluminum chamber are greater than those of either the quartz or steel chamber.

Blow off performance with air-jets having approximately the same mass flux ratio as the channel burners are shown in Figure 31. Even though the flame penetration can not be studied in an axisymmetric burner, perliminary observation

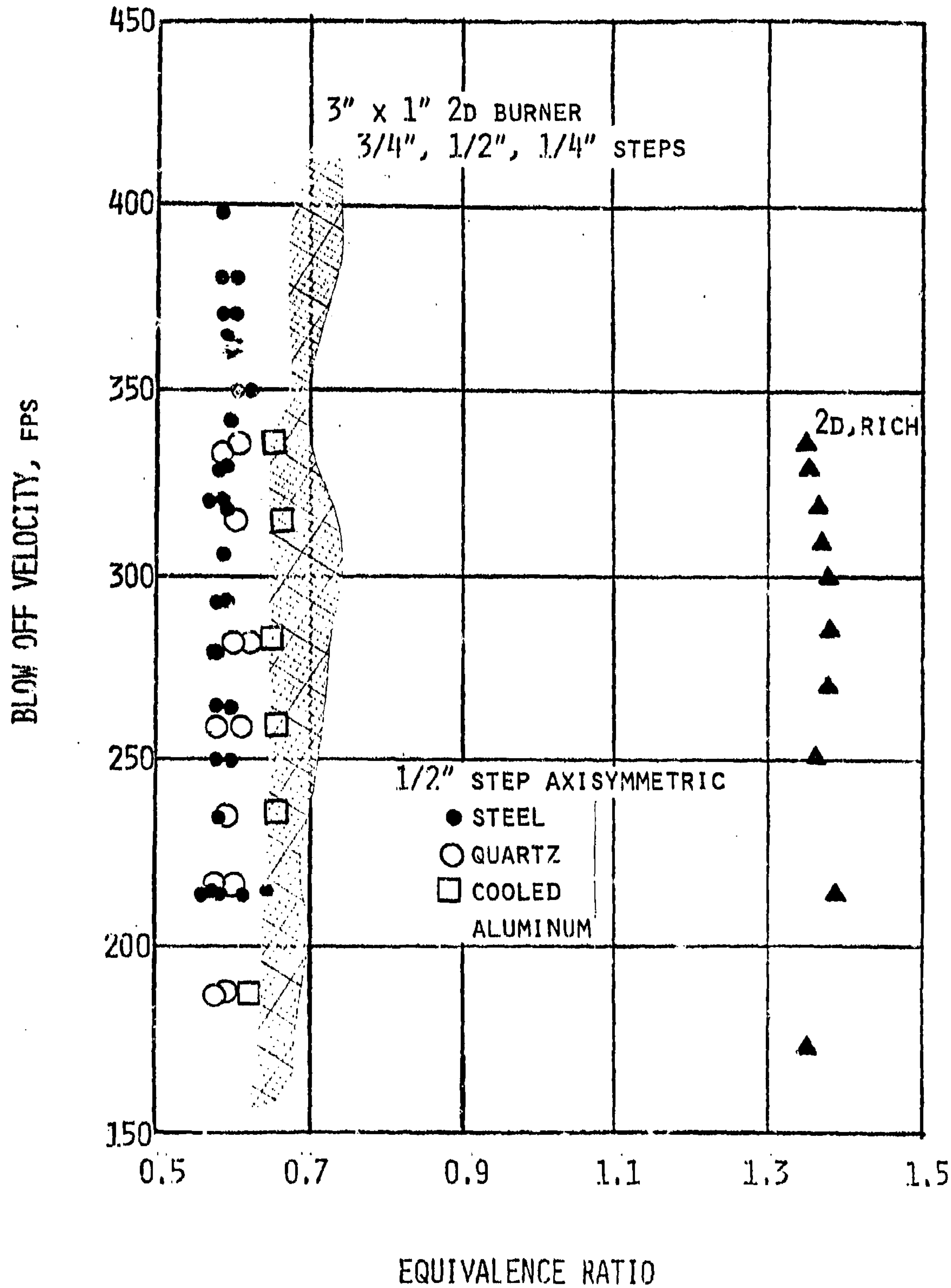

FIGURE 30 Blow off Limits of a 3" Diameter Axisymmetric Combustor. h = 1/2"

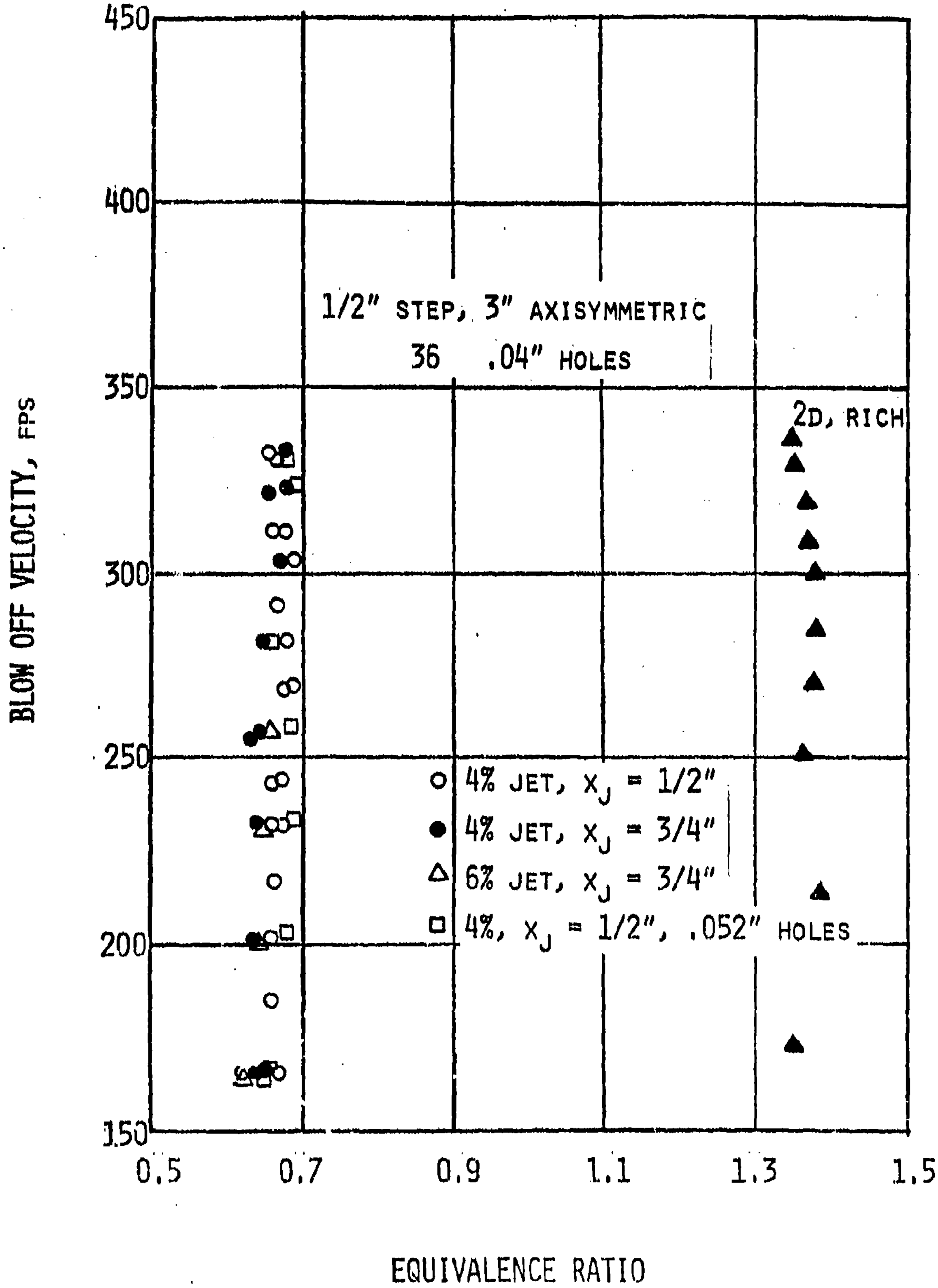

FIGURE 31 Blow off Limits of a 3" Axisymmetric Burner with Air Jets

indicates that the jets are effective in smoothing out rough burning caused by the location of the nozzle.

5.2. A 3" Diameter Cylindrical Burner With Swirl Jets

In this burner the jets perform the dual role of vortex amplifier as well as swirl generator. A jet system consisting of 24 .03" diameter holes at about 20° from the radial direction were used to generate the swirl in the system. Thus, instead of a set of guide vanes, the cross-jet system serves the function of swirl generator. Because of the swirl jets, this burner had the most stable behavior with respect to sudden small changes in operating conditions. Figure 32 compares the lean blow off limits of the swirl jet with those of normal jet systems. Smaller equivalence ratios at lean blow off are probably due to the additional recirculation zone near the center of the duct caused by the swirl-jets. In other configurations, the combustible mixture at the center of the duct near the sudden expansion step remains unburned. In the swirl burner, however, the additional recirculation zone at the center helps burn the otherwise unburned mixture.

A detailed study with different swirl angle is presently under way and will be reported at a later date.

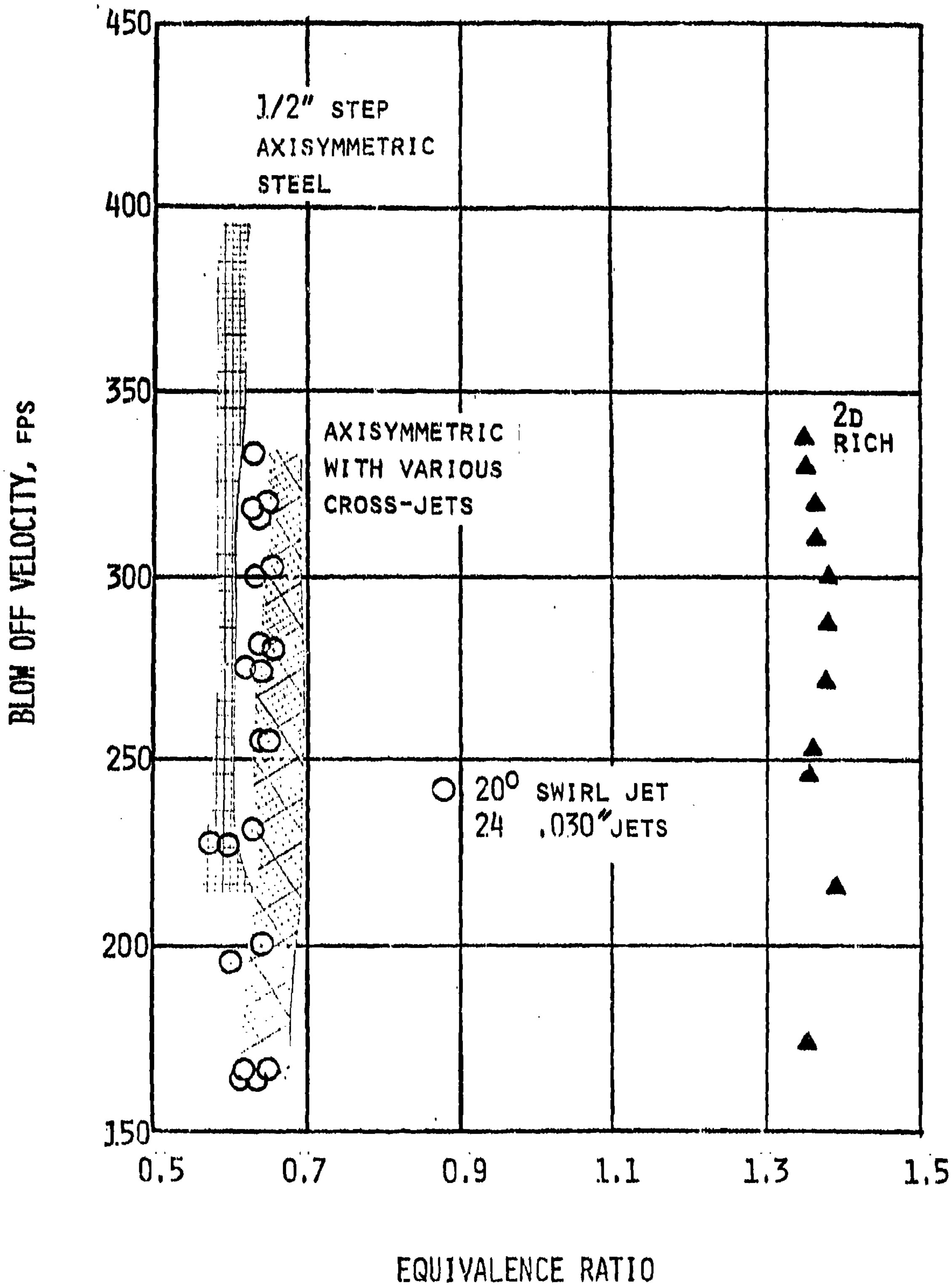

FIGURE 32 Blow off Limits of a 3" Axisymmetric Burner with Swirl Jets

5.3. Channel Burners with Multiple Steps and Multiple Jet Systems

Figure 33 shows the lean blow off data for a 3" x 1" burner with two 1/2" steps and two sets of jets located 1/2" upstream of the step. When two steps with only one jet system was used, the flame plume of the jet was observed to interfere with the flame stabilization process of the step directly opposite to the jets. Frequently, the flame at the step was blown off perhaps due to a large local velocity caused by the blockage resulting from the flame plume. This is a significant observation as far as the problem of geometric scaling is concerned. In other words, the characteristic height of the inlet must be larger than the flame penetration distance shown in Fig. 7.

The blow off data of Fig. 33 shows that even if malfunction causes blockage of one or two individual jets, the blow off performance of the burner is not unduly affected by it.

A 8" x 1" channel burner with the capability of four sets of jets on four effective steps was designed for studying geometric scaling. A sketch of the burner is given in Figure 34. However, the 12" diameter exhaust system proved completely inadequate in handling the large quantity of unburned propane air mixture. In spite of the

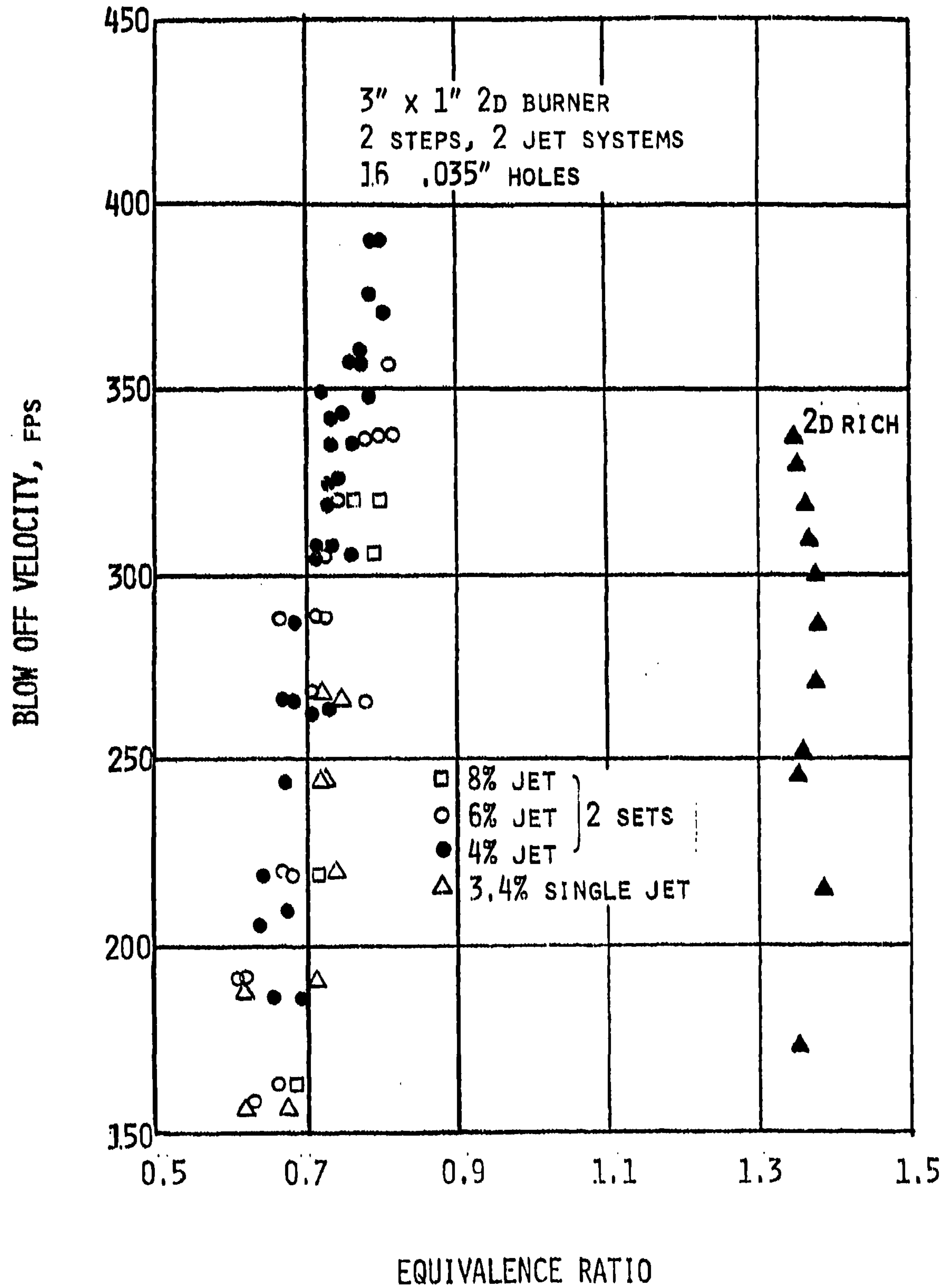

FIGURE 33 Blow off Limits of a 3" x 1", 2 Step, 2 Jet System Channel Burner

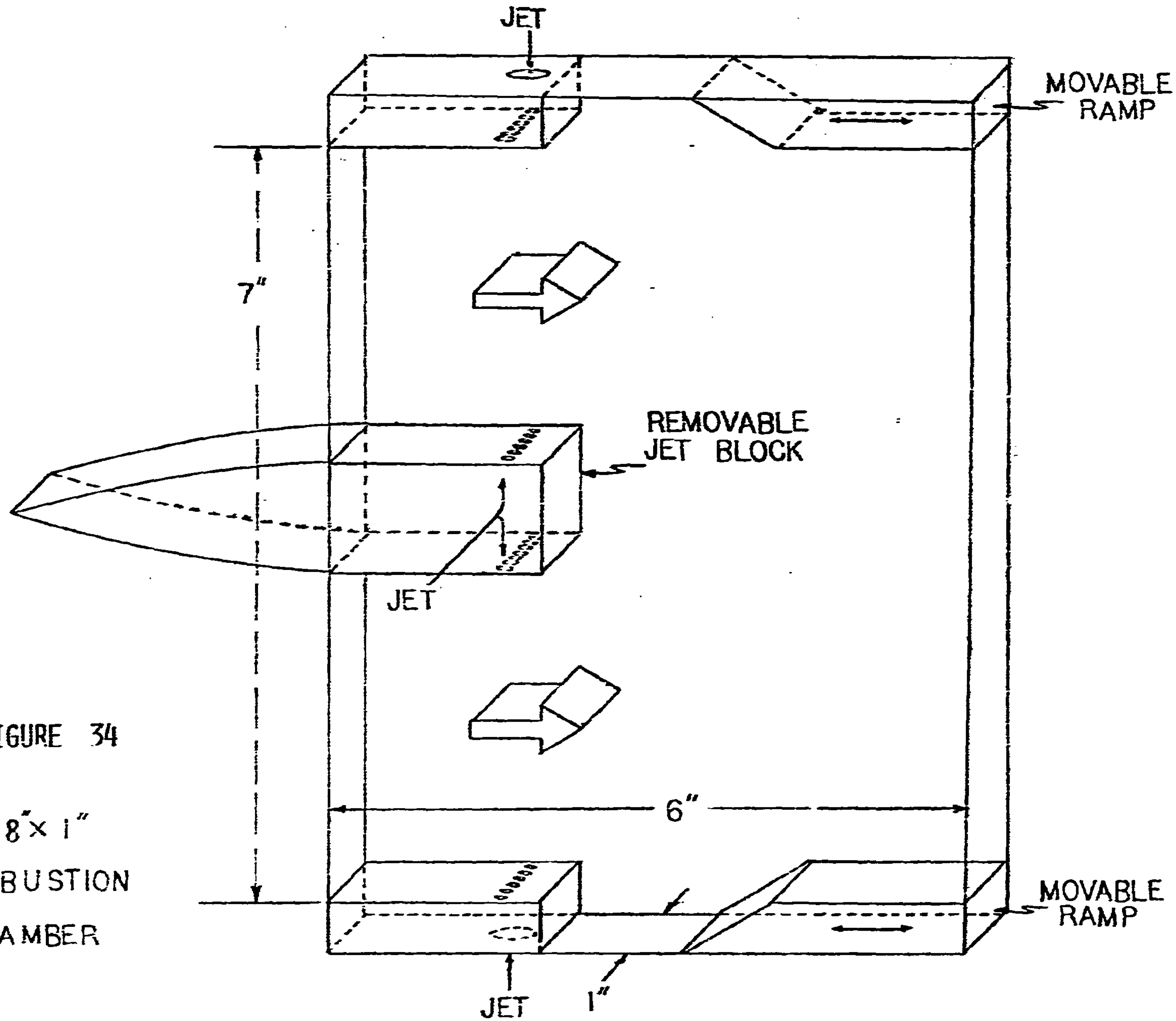

FIGURE 34

8" × 1"
COMBUSTION
CHAMBER

water spray, the combustible mixture consistently exploded inside the hot exhaust chamber and tended to flash back. Several lean blow off points at low velocities, however, were obtained before the experiments were terminated. Figure 35 compares the lean blow off points of an 8" x 1", 3" x 1" and 2" x 1 1/2" combustion chambers with sudden expansion steps. In spite of the difference in chamber size and characteristic lengths, all blow off data points seem to follow the same general trend. Because of the difficulty with the exhaust system only preliminary observations are made with four jet systems on four steps. Except for the large rate of heat release, the flame plumes appear very similar to the other channel burners.

5.4. Scaling - Preliminary Observations

If the free stream velocity and the nozzle to chamber area ratio are assumed to be fixed in a sudden expansion burner with premixed combustible mixture, the following list of characteristic dimensions can be considered in geometric scaling.

A_c = Chamber area, $f(L_c)$

A_i = Inlet area

A_j = Total jet area, $(n\pi d_j^2)/4$

n = No. of jets, d_j = Jet diameter.

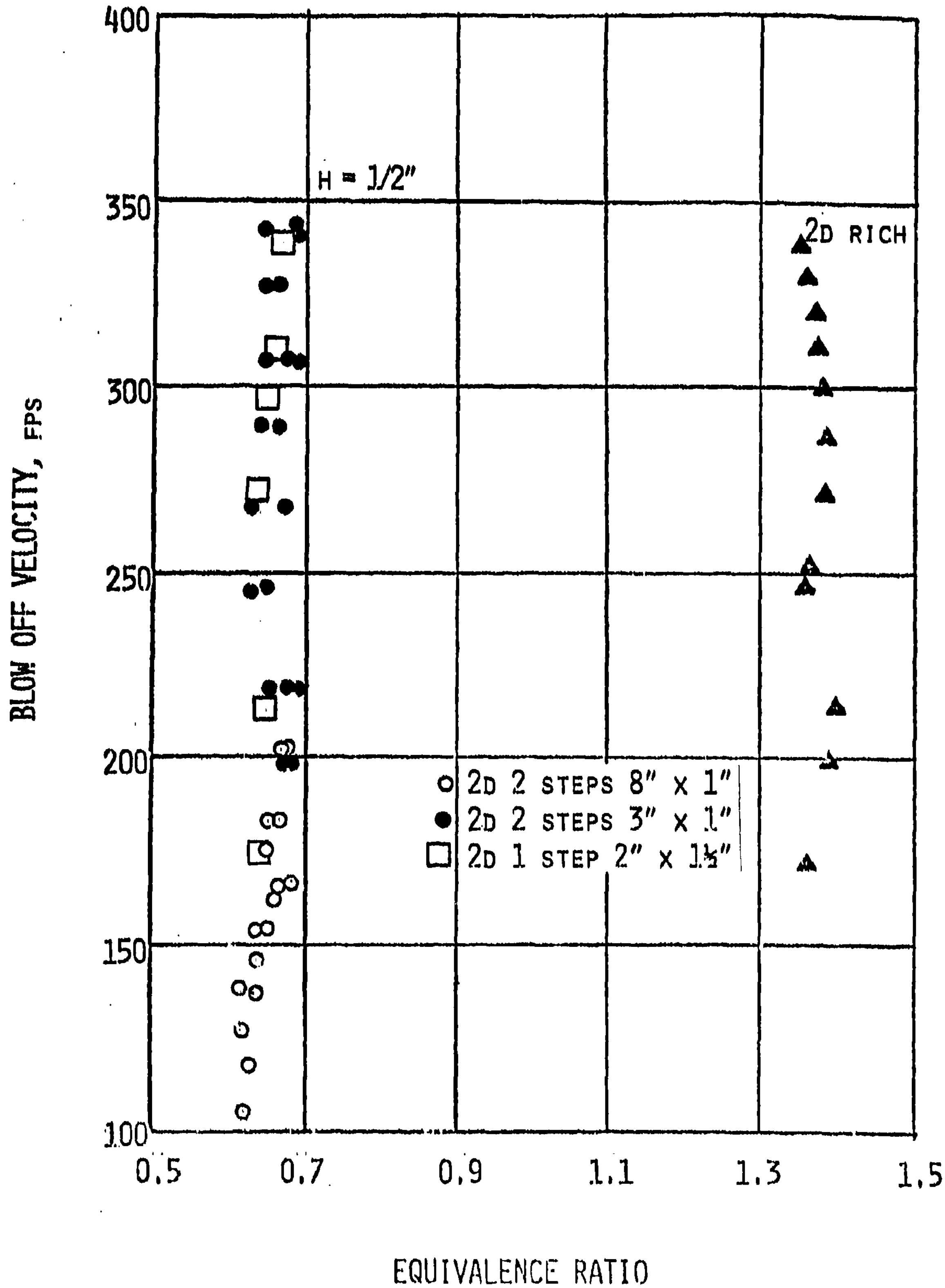

FIGURE 35 Blow off Data for 8" x 1", 3" x 1" and 2" x 1½" Sudden Expansion Burners

h = Step height

L = Distance to the nozzle

L_c = Characteristic height of the chamber

L_i = Characteristic height of the inlet

X_j = Location of the jet upstream of the step

X_r = Characteristic length of the recircualtion zone.

Y_p = Penetration height of the jet

Figure 36 shows the typical characteristic lengths of a sudden expansion burner.

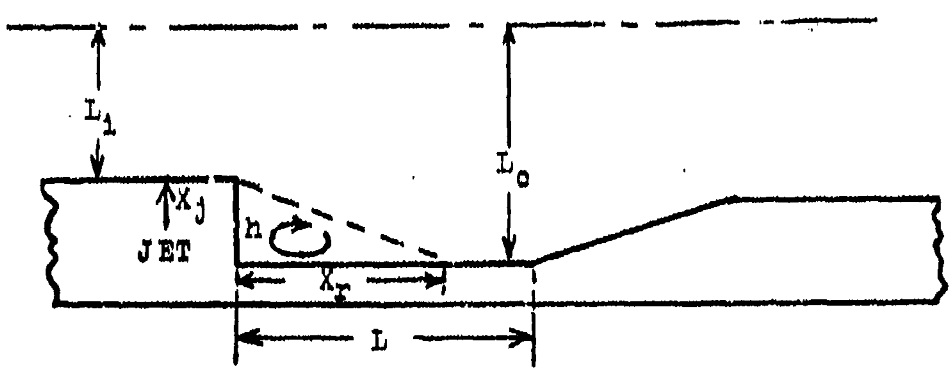

Figure 36 Characteristic lengths in a sudden expansion burner

Recirculation zone behind a flame holder is responsible for the process of flame stabilization. Therefore, its characteristic lenght X_r is of primary concern in geometric scaling. For a two dimensional system $X_r/h \sim 7$ in a trubulent flow is fairly well established. Even though such a value is not commonly quoted for an axisymmetric system, observation of the flame and qualitative study under cold flow conditions indicate that approximately the same value of 7* can be used for an axisymmetric system. Therefore, X_r can be assumed to scale directly with h for both two dimensional and axisymmetric systems. With burning, a lower limit of the recirculation volume exists which is consistent with stable flame holding at a given velocity, U_o and equivalence ratio $\emptyset$. Such a lower limit for the combustion chambers was found to correspond to $h = 1/4"$. For values of h smaller than 1/4" degradation of blow off performance was observed. As long as the step height is larger than 1/4" stable burner operation can be expected over a range of values. Degradation is again observed when $h \to \infty$. For all the burner configurations investigated during the course of the study, smooth and stable burning was observed for h values between 1/4" and 3/4".

* The exact value has not been determined. Preliminary results show a value between 7 and 10.

The location L of the nozzle can cause rough burning when $X_r > L$. Under such a condition, the nozzle interferes with the recirculation zone and causes an instability of the shear layer discussed in Section 3.3. In a two dimensional system rough burning has been initiated when $L/h \sim 3$ or smaller. For L/h values larger than 3 smooth burning has been observed in two dimensional systems. Qualitative observation indicates that rough burning in an axisymmetric system can be similarly initiated when the nozzle is located near the dump plane. Therefore, rough burning is one of the inherent characteristics of a small, volume-limited, compact dump burner. This is particularly true in a system when L/h is constrained in such a way that the nozzle interferes with the recirculation zone.

A system of cross-jets located upstream of the sudden expansion section has been shown to be effective in smoothing out rough burning in burners with small values of L/h. The location of the jets X_j is very critical for an optimum performance of the entire burner. The role of the jets as vortex amplifier requires a critical interaction distance between the jet and step induced vortices. $X_j \sim 0.5"$ was found to be the critical separation distance. This important parameter does not seem to scale with either L_c or L_i and is independent of the size of the system. Even though

no perceptible difference in blow off performance is indicated for a range of values of X_j, 0.5" appear to provide a rather stable operation against sudden small changes in the operating characteristics.

Flame penetration Y_p (Fig. 7) scales with the momentum flux ratio between the jet and the primary stream. In a burning system Y_p can not be increased indefinitely by increasing the momentum flux ratio. Excessive jet mass flow rate will cause too much dilution. Therefore, a critical mass flux ratio exists which must not be exceeded. For the choked, air-jet system at room temperature, stable burning is observed for mass flux ratio in the range 3 to 11. Since the mass flux ratio rather than the jet mass flow rate is the scaling parameter a large value of L_i will require a smaller jet mass flow rate. In the 3" x 1" chamber, for example, $\dot{m}_j/\dot{m}_a$ = 0.04 produced good results. For the 8" x 1" chamber, $\dot{m}_j/\dot{m}_a$ of 0.015 to 0.02 seemed to produce similar flame plume and burning. Therefore, in a larger chamber the jet system will cause a lower bleed penalty on the overall pressure loss.

Flame penetration Y_p resulting from a particular momentum flux ratio must be small compared to L_i so that no interference between the jet system will occur. In the 3" x 1" chamber with one set of jets and two steps,

Y_p was so large that the flame plume interfered with the flame stabilization process of the upper step. Cold flow studies in the 3" diameter chamber with a 2" diameter inlet dramatically shows the phenomenon of interference between jets. When 36 1/32" jets were used in the inlet section at $X_j = 0.5"$, because of jet interference the increase in the size of the zero velocity zone seemed to be too small for the momentum flux ratio. When 27 holes were blocked off and only 9 jets were active the interference was small and the increase in the size of the zero velocity zone was substantial (Fig. 29). When an axisymmetric chamber is scaled to a larger size its behavior in cold flow will approach that of the 9 jet system discussed earlier. Also with a larger radius its limiting form will be similar to the two dimensional system.

Table 5-1 lists the various parameters involved in scaling, their function and suggested range of values for design purposes. The number n of holes and diameter d_j of the jets are not included in the table. For a given engine with an available $\dot{m}_j$, the constraint of mass flux ratio specifies the total area A_j of the cross-jet system. Therefore, the number n of jets depends upon the spacing between the jets and the diameter d_j. A range of spacings between 0.1" to about 0.3" and a range of d_j between 0.03" and 0.05" gave satisfactory result in all the chambers

TABLF 5-1 SCALING PARAMETERS

PARAMETER	PHYSICAL FUNCTION	APPROXIMATE RANGE OF VALUES STUDIED	SCALABLE*	SUGGESTED VALUES FOR OTHER SIMILAR BURNERS
X_r	Describes the size of the recirculation zone	0.9"-6" without jet system. As much as 3 fold increase with jet system	YES (through h)	Depends upon the required size of the recirculation zone
Y_j	Interaction between vortices. Important for vortex amplification	0.1" - ∞	NO	0.5" ahead of the step for all cases
h	Size of the recirculation zone	1/8" - ∞	Yes, within a small range of values	1/2" to 3/4"
X_r/h	Size of the recirculation zone	Fixed. ∿ 7 without jets. As high as 20 with jets	NO	Depends upon the required size of the recirculation zone
L/h	Rough burning due to nozzle location	1 - ∞	NO	L/h > 5 without jets. Any value with jets
$\dot{m}_j/\dot{m}_a$	Vortex amplification	0.01 - 0.08	YES	Unspecified. Depends upon the burner size
$(\dot{m}_j A_i)/(\dot{m}_a A_j)$	Vortex amplification	Many discrete values	NO	3 - 11
$(\dot{m}_j A_i V_j)/(\dot{m}_a A_j V_a)$	Vortex amplification and flame penetration	Many discrete values	NO	20 - 80
L_i/Y_p	Harmful interaction between jets	1 - 3.5	NO	∿ 2
Jet stagnation pressure P_j	Jet air flow	15 - 60 psig	NO	Minimum p. which causes choked flow

* all characteristic lengths are uniformly changed.

investigated during the course of this study. It is not clear if the same range will be satisfactory in a much larger chamber. A test program with AFAPL is being planned now to obtain data on larger chambers.

VI DISCUSSION AND RECOMMENDATIONS

A system of discrete jets upstream of any flame holder can under certain conditions, significantly amplify the recirculation zone downstream of the flame holder. Experiments with sudden expansion burners show that the jet system with a mass flow rate upto about 4% of the primary flow rate is very effective in increasing flame spreading without sacrificing the blow off performance. Not only does the jet system significantly improve flame spreading, it is also capable of smoothing out rough burning caused either by fuel stratification or the presence of nozzle in a volume-limited burner. This behavior can be attributed to the amplification of the recirculation zone when the jet induced vortex is allowed to interact with the step induced vortex.

The ability to modulate the size of the recirculation zone by controlling the jet momentum flux is rather unique. It allows one to externally control the flame spreading, residence time and the allowable roughness of operation. In the case of a bluff body flame holder once a particular configuration for a given flow is selected, very little can be done to increase the strength of the vortex, flame spreading and the flame holding capability. Thus, the

use of a cross-jet system, helps create an advanced combustor with a variable strength flame holder. At lower vehicle speed during the early stages of flight little additional augmentation of flame spreading and flame holding is required. With increasing vehicle speed a stronger recirculation zone as well as increased flame spreading is necessary for the optimum performance of the propulsion system. Thus, by controlling the momentum flux of the cross-jet system, optimum operating condition can be maintained over the entire flight profile. All of this is achieved without any additional drag penalty.

When the jet system was used in the dual role of a vortex amplifier and swirl generator, the burner produced the best performance. Because of the swirl, an additional vortex at the center of the duct helps improve the operating behavior of the burner. Preliminary results with a 20° swirl-jet system are extremely encouraging.

Even though preliminary scaling parameters are listed in Table 5-1, experiments with larger chambers are absolutely essential before the scaling can be applied to a full size engine. Neither the air supply nor the exhaust system at USC are adequate for larger burners.

Most of the experimental work were carried out in quasi two dimensional channel burners. The use of these two

dimensional combustors with glass sides allowed visual observation of the system behavior and was very important in providing an excellent qualitative picture of the reacting flow field. The cold flow experiments in the same chamber gave additional valuable information on the role of the cross-jets as a vortex amplifier. These two dimensional burners are not simply laboratory tools. With the cross-jet system these are the limiting cases of an axisymmetric burner with a large radius of curvature. Cold flow experiments dealing with jet interference clearly indicated such a possibility (Fig. 29).

It is recommended that the following studies be continued

1. Use of the jets to amplify the recirculation zone and introduce swirl in the system. The flow field, blow off performance, rough burning and pressure drop in a variety of combustors should be studied.
2. Scaling study, similar to the one that is planned jointly with USC and AFAPL, should be pursued.
3. Instead of a premixed homogeneous system, fuel spray should be used to study the behavior of the droplets in the amplified recirculation zone.

4. The concept of vortex amplification should be explored in the study of combustion noise and burning characteristics of fuels with small reaction time. Slow burning fuels are expected to be compatible with the amplified recirculation zone which provides an increased residence time for the fuel species.

5. A more detailed spectral character of rough burning in a volume-limited combustor should be undertaken. The experiments dealing with the spectral content as described in this report are rather preliminary.

VII REFERENCES

1. Huellmantel, L. W., Ziemer, R. W. and Cambel, A. B., "Stabilization of Premixed Propane - Air Flames in Recessed Ducts," Jet Propulsion, 27, 1, pp. 31-43, January 1957.
2. Schaffer, A. B., and Cambel, A. B., "The Effect of an Opposing Jet on Flame Stability," Jet Propulsion, 25, 6, p. 284, June 1955.
3. Schaffer, A. B., and Cambel, A. B., "Continued Investigations of the Opposing Jet Flame Holder," Jet Propulsion, 26, 7, Part 1, p. 576, July 1956.
4. Duclos, D. P., Schaffer, A. B., and Cambel, A. B., "Flame Stabilizing Effects of Inclined Air Jets," Industrial and Engineering Chemistry, 49, 12, p. 2063, December 1957.
5. Choudhury, P. Roy and Lobell, M., "Experimental Investigation of a Modified Dump Combustor," 12th JANNAF Combustion Meeting, Newport, Rhode Island, August 1975. CPIA Publication 273, Vol. II, pp. 451 - 466, December 1975.

6. Choudhury, P. Roy and Lobell, M., "Status of the Modified Dump Combustor - A Variable Strength Flame Holder," 1976 JANNAF Propulsion Meeting, Atlanta, GA, December 1976. CPIA Publication 280, pp. 423-433, October 1976.

7. Choudhury, P. Roy, Lobell, M., Yep, F., and Chunn, T., "Feasibility of a Smooth Burning, Volume-Limited Dump Combustor," 13th JANNAF Combustion Meeting, Monterey, California, September 1976. CPIA Publication 281, Vol. III, pp. 207-220, December 1976.

8. Fetting, F., Choudhury, A. P. R. and Wilhelm, R. H., "Turbulent Flame Blow-off Stability. Effect of Auxiliary Gas Addition into Separation Zone," Seventh International Symposium on Combustion, Butterworths Scientific Publications, pp. 621-635, 1959.

9. Craig, R. R., and Stull, F. D., "Recent Status of Dump Combustor Investigations," Presented at the 1975 AFOSR Combined Contractors Meeting on Air Breathing Combustion Dynamics and MHD Power Generations and Lasers, July 7-10, 1975. Abstracts in AFOSR-TR-75 -0673.

10. Schmotolocha, S. N., and Economos, C., "Mixing and Combustion Mechanisms in High Speed Air Streams," Presented at the 1975 AFOSR Combined Contractors Meeting on Air Breathing Combustion Dynamics and MHD Power Generations and Lasers, July 7-10, 1975. Abstracts in AFOSR-TR-75-0673.

11. Heller, H. H., and Bliss, D. B., "The Physical Mechanism of Flow Induced Pressure Fluctuations in Cavities and Concepts for Their Suppression," AIAA 2nd Aero-Acoustics Conference, Hampton, VA., March 1975.

12. Choudhury, P. Roy and Lobell, M., "An Experimental Investigation of Rough Burning in a Dump Combustor of Small Volume," Paper No. 77-317, 15th AIAA Aerospace Sciences Meeting, Los Angeles, California, January 1977.

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An important practical application of the interaction of turbulent air jets with an impinging reacting stream is described in this report. A system of cross-jets located upstream of the sudden expansion step of a dump burner is able to amplify the recirculation zone thereby increasing the flame spreading as well as the characteristic residence time. Furthermore, the cross-jets with mass flow rates in the range of 1% to 4% are able to smooth out rough burning in a small volume-limited burner without any additional drag penalty. The lean blow off performance, rough burning, flow field characteristics and preliminary scaling

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parameters for a dump burner with a system of cross-jets are given. Preliminary study of a cross-jet system performing the dual role of a vortex amplifier and swirl generator shows a great promise. Because of encouraging results, recommendations are made to expand the activity to include swirl-jets in large combustors.